

# Threats to UK freshwaters under climate change: Commonly traded aquatic ornamental species and their potential pathogens and parasites

James Guildler<sup>1</sup>, Gordon H. Copp<sup>2,3,4,5</sup>, Mark A. Thrush<sup>1</sup>, Nicholas Stinton<sup>1</sup>,  
Debbie Murphy<sup>1</sup>, Joanna Murray<sup>2</sup>, Hannah J. Tidbury<sup>1</sup>

**1** *Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Weymouth, UK*

**2** *Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft Laboratory, Lowestoft, UK*

**3** *Department of Life and Environmental Science, Bournemouth University, Poole, UK*

**4** *Environmental and Life Sciences Graduate Program, Trent University, Peterborough, Canada*

**5** *Department of Ecology and Vertebrate Zoology, Faculty of Biology and Environmental Protection, University of Lodz, Poland*

Corresponding author: Hannah J. Tidbury ([hannah.tidbury@cefas.co.uk](mailto:hannah.tidbury@cefas.co.uk))

---

Academic editor: Marina Piria | Received 12 January 2022 | Accepted 24 May 2022 | Published 3 October 2022

---

**Citation:** Guildler J, Copp GH, Thrush MA, Stinton N, Murphy D, Murray J, Tidbury HJ (2022) Threats to UK freshwaters under climate change: Commonly traded aquatic ornamental species and their potential pathogens and parasites. In: Giannetto D, Piria M, Tarkan AS, Zięba G (Eds) Recent advancements in the risk screening of freshwater and terrestrial non-native species. NeoBiota 76: 73–108. <https://doi.org/10.3897/neobiota.76.80215>

---

## Abstract

The aquatic ornamental industry, whilst providing socio-economic benefits, is a known introduction pathway for non-native species, which if invasive, can cause direct impacts to native species and ecosystems and also drive disease emergence by extending the geographic range of associated parasites and pathogens and by facilitating host-switching, spillover and spill-back. Although current UK temperatures are typically below those necessary for the survival and establishment of commonly-traded tropical, and some sub-tropical, non-native ornamental species, the higher water temperatures predicted under climate-change scenarios are likely to increase the probability of survival and establishment. Our study aimed primarily to identify which of the commonly-traded non-native ornamental aquatic species (fish and invertebrates), and their pathogens and parasites, are likely to benefit in terms of survival and establishment in UK waters under predicted future climate conditions. Out of 233 ornamental species identified as traded in the UK, 24 were screened, via literature search, for potential parasites and pathogens (PPPs) due to their increased risk of survival and establishment under climate change. We found a total of 155 PPPs, the majority of which were platyhelminths, viruses and bacteria. While many of the identified PPPs were already known to occur in UK waters, PPPs currently absent from UK waters and with zoonotic potential were also identified. Results are discussed in the context of understanding potential impact, in addition to provision of evidence to inform risk assessment and mitigation approaches.



**Keywords**

Alien species, disease emergence, horizon scanning, invasive non-native species, risk screening

**Introduction**

The global trade in aquatic ornamental species is extensive, involving over 140 countries (Evers et al. 2019; Hood et al. 2019). Its value is estimated to be in the region of 15–30 billion US dollars annually, with a trade of 1.3 billion ornamental fishes reported (Evers et al. 2019; King 2019). The total value of live ornamental fishes imported into the UK in 2020 was £16.2 million (OATA 2020). The industry includes trade of both freshwater and marine ornamentals, however 76% of the 1244 metric tonnes of live fishes imported into the UK in 2020 were tropical freshwater fishes (OATA 2020). Though generally less well studied, invertebrates (including Mollusca and Crustacea) also represent an important group of traded aquatic ornamentals (Keller and Lodge 2007; Ng et al. 2016).

While the ornamental industry clearly provides economic and social benefits, it is a known pathway for the introduction of non-native species (NNS), pathogens and parasites, which pose a potential threat to aquatic biodiversity if they become invasive (Padilla and Williams 2004; Copp et al. 2005a; Peeler et al. 2011; Hood et al. 2019). Ornamental species are typically kept in closed systems, isolated from open waterways; but deliberate introduction into the wild, often the result of animals overbreeding or getting too large to house, or accidental introduction following escape, is known to occur (e.g. Courtenay 1999; Crossman and Cudmore 1999; Padilla and Williams 2004; Copp et al. 2005b; Duggan et al. 2006; Wood et al. 2022). Introductions of NNS can drive disease emergence by extending the geographic range of associated parasites and pathogens, and by facilitating host-switching or via spillover and spill-back (Peeler et al. 2011). Outbreaks of Koi Herpes Virus (KHV) and Spring Viraemia of Carp (SVC) in UK fisheries, which resulted in substantial mortalities in common carp *Cyprinus carpio carpio* L. 1758 and economic losses, have been linked to the introduction of koi carp *C. carpio koi*, an ornamental variety of common carp (Taylor et al. 2010, 2011, 2013).

In recognition of the threat posed by live non-native fishes, legislation that restricts the keeping of live fishes is in place in the UK. Key legislation includes ‘The Prohibition of Keeping or Release of Live Fish (Specified Species) (England) Order 2014’ (and its predecessors in 1998 and 2003) implemented under the ‘Import of Live Fish (England and Wales) Act 1980’, and ‘The Keeping and Introduction of Fish (England and River Esk Catchment Area) Regulations 2015’. These legislative instruments apply primarily (if not exclusively) to freshwater fishes, prohibiting their keeping in England without a licence, with similar powers applying in Wales, Scotland and Northern Ireland. The original 1998 Order listed only species considered to be of concern at that time, with the 2003 Order extending the list to include some additional species. These



orders were perhaps the most advanced of their kind in Europe and North America (Copp et al. 2005a). The 2014 Order took a much wider approach, with the schedule listing all taxonomic Orders that contained freshwater fish species and stating that all non-native freshwater fishes required a licence to be kept with the exception of those (primarily native species) listed in the 2014 Order's annexes. However, two general licences have been issued permitting the keeping of fishes in garden ponds and/or indoor aquaria. The first, defined here as the 'garden pond fish list' (UK Government 2021a) details standard ornamental pond fishes, namely koi carp, goldfish *Carassius auratus* L. 1758, orfe *Leuciscus idus* L. 1758, grass carp *Ctenopharyngodon idella* Cuvier & Valenciennes, 1844 and sturgeon (*Acipenser* spp.), permitted to be kept in aquaria or secure outdoor garden ponds. The second, defined as the 'ornamental fish list' (UK Government 2019), comprises mainly tropical and subtropical genera (and in some cases species), which are considered to pose a low risk of becoming established or invasive in UK waters, and permitted to be kept in indoor aquaria only. Parallel legislation exists in relation to crayfish in the form of the 'Prohibition of Keeping of Live Fish (Crayfish) Order 1996', which only permits the keeping of red-clawed crayfish *Cherax quadricarinatus* Von Martens, 1868 for ornamental purposes under a general licence and for the use of all non-native fishes in fisheries in the form of 'The Keeping and Introduction of Fish (England and River Esk Catchment Area) Regulations 2015'. Legislation also exists to prevent the introduction of NNS in to the wild (e.g. Wildlife and Countryside Act 1981), and to limit activities associated with specific NNS (e.g. Invasive Alien Species (Enforcement and Permitting) Order 2019). Further, in relation to aquatic animal disease risk specifically, under 'The Aquatic Animal Health (England and Wales) Regulations 2009', live aquatic animal imports require certification.

Currently, UK temperatures are typically below those necessary for the survival and establishment of the commonly-traded tropical, and some sub-tropical, ornamental fishes (species on the ornamental fish list). However, elevated water temperatures (a 2 °C increase) forecasted by future climate change scenarios are predicted to increase the probability of survival and establishment for some existing fish species (Britton et al. 2010). Hence there may be an increased risk of pathogen and parasite introductions, transmissions and disease emergence events (Marcos-López et al. 2010). Climate modelling under four different Representative Concentration Pathway (RCP) scenarios, *sensu* Moss et al. (2010), indicates that global mean surface temperature may increase by between 0.4 and 2.6 °C by the mid-21<sup>st</sup> century (Moss et al. 2010; Van Vuuren et al. 2011; Nazarenko et al. 2015). An understanding of the trade in ornamental species, and potential disease threats associated with commonly-traded species that may have an increased risk of establishment in the wild under future climate conditions, is essential to mitigate threats and protect aquatic biodiversity, and ensure the sustainability of an important industry.

The aim of our study was to identify commonly-traded non-native (NN) ornamental fishes, crustacea and molluscs at increased risk of survival and establishment in UK waters under elevated temperatures predicted by climate change forecasting. Further, applying the workflow proposed by Foster et al. (2021), organisms known,



or with potential to be, pathogenic or parasitic that have been observed associating with these NN ornamental species at any point in the ornamental fish trade pathway were identified. Applications of the outcomes to inform risk assessment and mitigation measures to protect and sustain the ornamental industry in the long term are discussed.

## Methods

Records of commonly imported species, such as packing lists that document details of ornamental species imported via the Heathrow Border Control Post (BCP), were not available for use during this study. Therefore, to identify the NN freshwater ornamental species most commonly-imported into UK, a proxy measure was adopted that combined outputs from three different, but complementary methodologies: expert elicitation, eBay retailer search and Google search.

Expert elicitation involved use of the list, provided by the Ornamental Aquatic Trade Association (OATA; <https://ornamentalfish.org/>), of ornamental species/genera considered by OATA to be the most commonly traded in the UK (by volume). Further, a short list of those NN ornamental species most likely to establish in UK, i.e. species from warm temperate or sub-tropical climatic zones, was provided by the Fish Health Inspectorate (FHI) for England and Wales.

A list of ornamental live-fish retailers was constructed from an eBay search carried out on 8 October 2020 using the term ‘live fish’. Search results were filtered for NN fishes that fell under the water type categories of ‘fresh’, ‘pond’, ‘all water types’ and ‘not specified’. Species were recorded from all listings between 9 September and 8 October 2020, inclusive. The total number of listings for each NN fish species was used as a proxy measure of trade volume. A separate eBay search using the term ‘live invertebrates’ was carried out on 13 October 2020. Search results were filtered for NN invertebrates that fell under the water type categories of ‘fresh’, ‘pond’, ‘all water types’ and ‘not specified’. Initial results indicated that significantly fewer invertebrate species were listed compared to fish species. Therefore, all NN invertebrate species listings returned by the search, with no restrictions on the date, were recorded. The number of listings per NN invertebrate species was not recorded and species listed multiple times were recorded only once.

A Google search was carried out on 20 October 2020 using the term ‘fish species for cold or unheated aquaria’, and this provided information on popular ornamental fish species likely to be traded in the UK. Although returning primarily temperate species, it also included tropical fish species with wide temperature tolerances, which therefore do not require heated aquaria, e.g. Endler’s livebearer *Poecilia wingei* Poeser, Kempkes & Isbrücker, 2005, and zebra danio *Danio rerio* Hamilton, 1822 (López-Olmeda and Sánchez-Vázquez 2011). In the search for cold or unheated aquaria species, the most popular NN fish species listed in the first 20 websites or blogs (See Suppl. material 1: List S1) were used to represent commonly-traded species. All species mentioned were recorded only once.



A master list of species' common and scientific names was developed. If the species scientific name was absent in the eBay listing or on the website/blog, then it was searched for (using the common name) on FishBase ([www.fishbase.se/search.php](http://www.fishbase.se/search.php)) for all fish species or via a google search for the invertebrate species. Where fishes and invertebrates were not identified to species level, the entry was removed from the master list. Species recorded via any of the methodologies were collated into the single master list (See Suppl. material 1: Table S1).

The master list was refined by removal of species, based on the following criteria: i) the NN species is present on the 'garden pond fish list' or is not present on the 'ornamental fish' list under The Prohibition of Keeping or Release of Live Fish (Specified Species) (England) Order 2014; and ii) the NN species is recorded as present within UK waters on the Global Biodiversity Information Facility (GBIF; [www.gbif.org](http://www.gbif.org)). Although climate change may increase the risk of some of these NNS, either increasing their current range or establishing new populations as a result of further introductions, the associated pathogen risk was considered to exist already because the species is already present.

## Data analysis and modelling

To aid the selection of species for potential pathogen and parasite (PPP) screening, a high-level estimation of climate suitability for each NNS on the master list was undertaken using a species distribution modelling (SDM) approach. Note that the term potential 'pathogen or parasite' is used as a catch-all term, given that evidence for pathogenic or parasitic association was not extensively reviewed in the present study and in fact is often unavailable, in particular for novel environments or hosts. The development of SDMs involved selection of temperature variables under the current climate (2020) and, under future climate, represented by an intermediate climate change scenario, the RCP 4.5 scenario, which predicts stabilisation of radiative forcing (Van Vuuren et al. 2011) and an increase in global annual mean surface air temperature of between 1 and 2 °C (Nazarenko et al. 2015).

The global distribution for each species on the master list was obtained from the GBIF. The climatic zone classification sub-tropical or temperate and the native continent(s) were determined using FishBase. No equivalent database to FishBase exists for invertebrates, so the native range of each invertebrate species was determined via a Google search, and the climatic zone of each range was then climate classified by matching the invertebrate species with fish species from a similar range. Species classified as subtropical or temperate, or with an occurrence record on the GBIF that was outwith the tropical bands (i.e. between the tropics of Capricorn and Cancer), were selected for further analysis (See Suppl. material 1: Table S2). The total number of geo-referenced occurrences for the selected species was recorded. To reduce bias of repeated sampling or multiple reports of a species within the same location, only one record per coordinate was included in the analysis. Species with <100 geo-referenced records were excluded from further analysis (See Suppl. mate-



rial 1: Table S1). A threshold of 100 geo-referenced records balanced the accuracy of suitability model outputs and number of species for which models could be run. For each species, occurrence data were cleaned using the CoordinateCleaner package in R (Zizka et al. 2019); this package includes a wrapper function that identifies and removes potential errors in the data based on: country and coordinate mismatches, coordinates at sea, zero coordinates, coordinates assigned to country centroids and significant outliers.

Global climate variables at a spatial resolution of ten arc-minutes were downloaded for the present day from the WorldClim dataset (<http://worldclim.org>) – these are observed data that have been interpolated from current climatic conditions recorded by weather stations (Hijmans et al. 2005). Six temperature variables were then selected for the species distribution models: 1) Annual mean temperature; 2) Mean diurnal range (Mean of monthly: max temp – min temp); 3) Max temperature of warmest month; 4) Min temperature of coldest month; 5) Mean temperature of warmest quarter; and 6) Mean temperature of coldest quarter. Future climate projections were downloaded from the WorldClim dataset. These are derived from five bias-corrected CMIP5 Global Climate Models (GDFL-CM3, HadGEM2-CC, MIROC5, INM-CM4.0, and CSSM4) which specifically related to the 2050 projection (mean for 2041–2060) of the RCP 4.5 climate change scenario.

Species distribution models (SDMs) were employed for NNS on the refined master list to predict the potential suitability of the UK climate for the NNS with respect to the selected temperature variables, both under current (2020) and future climate conditions (in 2050), as represented by climate change scenario RCP 4.5 (Moss et al. 2010). The SDMs were run in R using the SDM package (Naimi and Araújo 2016). Occurrences used in the SDMs were limited to a maximum of 1000 per species. Pseudo-absences were then assigned to each species. The number of pseudo-absences was not fixed across species, rather the number of pseudo-absences was equal to the number of occurrence records for that species as suggested for classification techniques by Barbet-Massin et al. (2012). No pseudo-absence was assigned to a coordinate representing a presence occurrence. Both presences and pseudo-absences input into the SDMs were restricted to the continent within which the native range of the species occurs. For species with distributions that extend across more than one continent, presences and pseudo-absences from all relevant continents were input into the SDMs.

Ensemble models were built for current climate conditions by using two different machine learning methods (boosted-regression trees and random forests). These models estimated the effects of the selected temperature variables, for the present day, on the distribution of each species within the continent of their native range. As no data were available to evaluate the model predictions independently, data were split at random into training (70%) and test data (30%). This random split of the data was repeated five times. To account for the influence of pseudo-absences on model outputs, five random and independent pseudo-absence sets were generated. In total,



50 model replicates were run (two modelling techniques × five pseudo absences × five split samplings) for each species. A geographical representation of the UK was created by cropping a rectangular area using the drawExtent function, which was split into 3828 ten arc-min grid cells ( $\approx 340 \text{ km}^2$ ). A suitability score for each species, was predicted for each grid cell using the un-weighted ensemble models, with scores ranging from 0 to 1. A suitability score of 1 indicates that the model predicts the presence of the species in a given location and a score of 0 indicates that the model predicts the absence of the species in that location, based solely on temperature predictors. An overall UK suitability score for each species, for both the present day and under the 2050 scenario, was then calculated by taking the mean of all grid cell suitability scores. Species with a mean suitability score of  $\geq 0.15$  in 2050 were selected for parasite/symbiont screening.

Consistent with the framework outlined by Foster et al. (2021), PPP screening consisted of (Table 1): i) organisms associated with each species, i.e. those classified as pathogens, parasites or symbionts, were searched for on PubMed; ii) the associated organisms revealed in the first two pages of a Google search result (using the following terms and format: “*species name*” AND pathogen OR parasite OR commensal OR symbiont OR protist OR bacteria OR virus) were screened for information supplementary to that provided through the PubMed search; and iii) search results were categorised into two groups – PPPs reported to be associated with (or infect) species at any point within the ornamental trade pathway, including wild sourcing (i.e. natural host-PPP interactions), and PPPs known to infect the species through laboratory challenge studies only. Where possible, whether the host-PPP interaction was associated with sub-clinical or asymptomatic infection, clinical signs of disease and/or mortality were noted. Additionally, the country of observation and the point in the ornamental fish trade pathway (e.g. wild, farm, retailer, hobbyist etc.) were recorded.

**Table 1.** The process undertaken to find information on pathogens, parasites and symbionts associated with each species, with a suitability score of  $\geq 0.15$ , on PubMed. Only steps one to three were carried out in the present study (adapted from Foster et al. 2021).

Step 1	Search full species name in [All Fields]. If 0, then go to 2, if $\geq 1$ , then go to 3
Step 2	Search genus name in [All Fields]. If 0, then decide whether continuing at a higher taxonomic level, is appropriate. If $\geq 1$ , go to 4.
Step 3	Conduct search using the criteria: ( <i>Species name</i> [All Fields]) AND (microbiome[Title/Abstract] OR symbio*[Title/Abstract] OR pathogen*[Title/Abstract] OR parasit*[Title/Abstract] OR protist[Title/Abstract] OR protozoa[Title/Abstract] OR bacteria*[Title/Abstract] OR virus[Title/Abstract] OR host[Title/Abstract] OR reservoir[Title/Abstract] OR vector[Title/Abstract] OR infection [Title/Abstract]) Scan papers for pathogen/symbiont reports and IDs and record
Step 4	Conduct search using criteria: ( <i>Genus name</i> [All Fields]) AND (microbiome[Title/Abstract] OR symbio*[Title/Abstract] OR pathogen*[Title/Abstract] OR parasit*[Title/Abstract] OR protist[Title/Abstract] OR protozoa[Title/Abstract] OR bacteria*[Title/Abstract] OR virus[Title/Abstract] OR host[Title/Abstract] OR reservoir[Title/Abstract] OR vector[Title/Abstract] OR infection [Title/Abstract]) Scan papers for pathogen/symbiont reports and IDs and record
Step 5	Engage with taxon group specialists, as appropriate, to sense check & compile additional information.



## Results

### Commonly-traded species

The master list of species commonly imported to the UK contained 193 species of ornamental fish, and 40 species of ornamental invertebrate, (total 233, See Suppl. material 1: Table S1). A total of 160 fish species were removed from the master list, and not subject to suitability scoring, because they met at least one of the following criteria: i) present on the list of ‘garden pond’ fishes, ii) absent from the list of ‘ornamental fish’ species or recorded as present in the UK on the GBIF, iii) low number (<100) of GBIF records, or iv) distribution was restricted to within the tropical bands (See Suppl. material 1: Table S1).

A total of 32 invertebrate species were removed from the master list because they met at least one of the following criteria: i) species list or recorded as present in the UK on GBIF, ii) low number (<100) of GBIF records, iii) distribution was restricted to within the tropical bands. One further invertebrate species, *Pomacea maculata* Perry, 1810 (synon. *P. insularum*), was removed from the master list because all *Pomacea* spp. were banned from import into the UK (OATA 2021; UK Government 2021b) at the time of our study (See Suppl. material 1: Table S1). Therefore, the refined master list subjected to suitability analysis comprised 33 fish and seven invertebrate species (Table 2).

The majority of fish species (30.3%;  $n = 10$ ) on the refined master list belong to the Order Cypriniformes, which includes the loaches, carps, barbs and minnows; taxa that are common in the aquarium trade. A notable proportion of the fish species on the refined master list (21%;  $n = 7$ ) are the smaller ray-finned fishes of the Order Cyprinodontiformes, such as killifishes and livebearers (e.g. mollies, guppies), which are popular aquarium fishes. Also common on the refined master list are species of the taxonomic orders Siluriformes (18.1%;  $n = 6$ ), representing the catfishes, and Cichliformes (15.1%;  $n = 5$ ), representing the cichlids and angelfishes. Invertebrate species on the refined master list comprise snails, crabs, shrimps and a crayfish. Three were of the taxonomic Order Decapoda (Table 2). Species within orders Notostraca and Cy-cloneritida are also present on the list.

### Species estimates of UK temperature suitability

Mean UK suitability scores for the fish species ranged from 0.08 to 0.59 under current climate conditions and 0.08 to 0.62 under future (2050) climate conditions (Table 2). The highest suitability score in 2050 was seen for the dojo loach *Misgurnus anguillicaudatus* Cantor, 1842, and the Japanese rice fish *Oryzias latipes* Temminck & Schlegel, 1846 (Table 2, also see Suppl. material 1: Fig. S1). Although there was no difference in suitability between current day and 2050 for 15 fish species, suitability increased (mean increase in suitability of 0.05) for 15 fish species. The greatest increase



**Table 2.** Outputs of species distribution models (SDMs), using UK temperatures under current and future climate conditions (i.e. 2050, under Representative Concentration Pathway, RCP 4.5, scenario), for ornamental freshwater fish and invertebrate species identified via eBay and Google searches in addition to expert elicitation as commonly traded in the UK (ordered by decreasing mean RCP 4.5 suitability score, then by mean current day suitability score and then by native continent. Also given is the number of records (*n*) from the Global Biodiversity Information Facility (GBIF; [www.GBIF.org](http://www.GBIF.org)) used to carry out the SDMs (after selection of 1000 random points, removal of duplicates and cleaning). Species in bold had a mean suitability score of  $\geq 0.15$  under RCP4.5 2050 and were therefore subject to pathogen and parasite screening.

Taxon group/Scientific name	Common name	Native Continent	n	Current	RCP 4.5
<b>FISHES</b>					
<i>Misgurnus anguillicaudatus</i>	dojo loach	Asia	781	0.59	0.62
<i>Oryzias latipes</i>	Japanese rice fish	Asia	247	0.53	0.58
<i>Aphanius mento</i>	pearl-spotted killifish	Asia	135	0.35	0.38
<i>Rhodeus ocellatus</i>	rosy bitterling	Asia	311	0.23	0.32
<i>Pimephales promelas</i>	fathead minnow	North America	859	0.19	0.31
<i>Enneacanthus chaetodon</i>	black banded sunfish	North America	177	0.23	0.29
<i>Misgurnus mizolepis</i>	Chinese muddy loach	Asia	244	0.26	0.28
<i>Garra rufa</i>	red garra	Asia and Europe	234	0.25	0.28
<i>Notropis chrosomus</i>	rainbow shiner	North America	376	0.26	0.27
<i>Amatitlania nigrofasciata</i>	convict cichlid	North America	487	0.21	0.26
<i>Xiphophorus variatus</i>	variable platy	North America	276	0.15	0.20
<i>Pethia conchonius</i>	rosy barb	Asia	128	0.17	0.19
<i>Xiphophorus hellerii</i>	swordtail	North America	943	0.13	0.17
<i>Paracheirodon axelrodi</i>	cardinal tetra	South America	129	0.17	0.17
<i>Corydoras paleatus</i>	pepper corydoras	South America	126	0.15	0.16
<i>Barbodes semifasciolatus</i>	gold barb	Asia	141	0.16	0.15
<i>Astronotus ocellatus</i>	oscar	South America	241	0.16	0.15
<i>Osteoglossum bicirrhosum</i>	arawana	South America	126	0.15	0.15
<i>Phractocephalus hemiliopterus</i>	redtail catfish	South America	120	0.14	0.14
<i>Pethia ticto</i>	ticto barb	Asia	113	0.13	0.13
<i>Hypostomus plecostomus</i>	suckermouth catfish	South America	277	0.13	0.13
<i>Hypseleotris compressa</i>	empire gudgeon	Australasia	855	0.11	0.12
<i>Pygocentrus nattereri</i>	red bellied piranha	South America	532	0.12	0.12
<i>Poecilia reticulata</i>	guppy	North & South America	936	0.11	0.11
<i>Corydoras aeneus</i>	bronze corydoras	South America	278	0.12	0.11
<i>Melanotaenia nigrans</i>	black-banded rainbowfish	Australasia	212	0.10	0.10
<i>Amphilophus citrinellus</i>	midas cichlid	North America	193	0.10	0.10
<i>Cyprinella lutrensis</i>	red shiner	North America	902	0.10	0.10
<i>Rocio octofasciata</i>	Jack Dempsey	North America	595	0.10	0.10
<i>Pterophyllum scalare</i>	angelfish	South America	152	0.10	0.10
<i>Poecilia velifera</i>	sail-fin molly	North America	175	0.09	0.09
<i>Vieja melanura</i>	redhead cichlid	North America	706	0.09	0.09
<i>Poecilia sphenops</i>	common molly	North & South America	519	0.08	0.08
<b>INVERTEBRATES</b>					
<i>Palaemonetes paludosus</i>	ghost shrimp	North America	249	0.31	0.35
<i>Tarebia granifera</i>	quilted melania	Asia & Australasia	160	0.26	0.28
<i>Cherax quadricarinatus</i>	redclaw crayfish (blue lobster)	Australasia	108	0.22	0.22
<i>Triops australiensis</i>	tadpole shrimp	Australasia	145	0.21	0.21
<i>Neritina pulligera</i>	dusky nerite	Africa, Asia & Australasia	111	0.18	0.19
<i>Marisa cornuarietis</i>	Colombian ramshorn apple snail	North & South America	195	0.15	0.17
<i>Metasesarma aubryi</i>	red apple crab	Asia	312	0.13	0.13



in suitability score was seen for the fathead minnow *Pimephales promelas* Rafinesque, 1820, whose score increased by nearly 63% from 0.19 to 0.31. For three fish species, suitability scores reduced between the current day and 2050, though by only a small amount (Table 2): gold barb *Barbodes semifasciolatus* Günther, 1886, bronze corydoras *Corydoras aeneus* Gill, 1858 and the oscar, *Astronotus ocellatus* Agassiz, 1831.

Mean suitability scores for the invertebrate species ranged from 0.15 to 0.33 and from 0.17 to 0.44 under current day and 2050, respectively (Table 2). The highest suitability score in 2050 was seen for the ghost shrimp *Palaemonetes paludosus* Gibbes, 1850. In total, four invertebrate species showed a small increase in suitability score between the present day and 2050. No difference in suitability score between current day and 2050 was seen for three species: red-clawed crayfish, tadpole shrimp *Triops australiensis* Spencer & Hall, 1895, and red apple crab *Metasesarma aubryi* A. Milne-Edwards, 1869. In contrast to fishes, a reduction in suitability in 2050 was not seen for any of the listed invertebrate species.

## Potential pathogen and parasite screen

In total, 18 fish and six invertebrate host species were screened for potential pathogens and parasites based on their suitability score of  $\geq 0.15$  under RCP 45 2050. A total of 504 records were returned from the literature (PubMed and Google) search. The number of records against each screened host species ranged between 0 and 144, with four species (tadpole shrimp; black banded sunfish *Enneacanthus chaetodon* Baird, 1855; rainbow shiner *Notropis chrosomus* Jordan, 1877; dusky nerite *Neritina pulligera* L., 1767) returning no records. A total of 243 records were deemed unsuitable for the PPP screen following review of the abstract to assess whether or not the publication included both the host species and/or a PPP. In total, 163 records documented natural interactions between hosts and PPPs (Table 3) and 98 records reported host species susceptibility to PPP infection under laboratory conditions (See Suppl. material 1: Table S2).

In total, 155 PPPs across four biological kingdoms (Animalia, Fungi, Prokaryotes and Protists) and two domains (Bacteria and Viruses) were identified as associated with the screened host species. The majority belonged to phyla within the Animalia kingdom (66%;  $n = 100$ ), specifically Acanthocephala (2%,  $n = 3$ ), Annelida (1%,  $n = 2$ ), Arthropoda (6%,  $n = 10$ ), Cnidaria (1%,  $n = 2$ ), Nematoda (10%,  $n = 16$ ), and Platyhelminthes (43%,  $n = 67$ ) (Table 3).

Viruses represented 12% of the total PPPs identified as associated with screened host species, and they belonged to a number of RNA virus families, including *Rhabdoviridae*, *Birnaviridae*, as well as the DNA virus family, the iridioviruses (Table 3). Evidence suggests that a large proportion of the viruses identified can cause clinical disease (72%) and/or mortality (56%) in potential hosts screened. Sub-clinical infection by some viruses was also reported to be present in some of the screened potential hosts. Bacterial PPPs represented 11% of PPPs associated with screened hosts and belonged



to a number of groups including Aeromonads, *Mycobacterium*, *Vibrio* and *Streptococcus*, and these were largely opportunistic bacteria, which are commonly associated with disease (88%) and mortality (84%) across a wide range of species (Table 3).

The greatest number of PPPs were reported for fathead minnow, with 27 in total (Table 3). Screening also highlighted 25 PPPs associated with dojo loach, 17 PPPs associated with red-claw crayfish and 12 PPPs associated with red garra *Garra rufa* Heckel, 1845.

Many of the PPPs found to be associated with the screened host species are known to already occur in UK waters. In particular, species of bacteria associated with screened hosts have a wide global distribution and are likely already associated with disease in aquatic organisms in the UK. Also known to cause disease in the UK is the protist *Ichthyophthirius multifiliis* Fouquet, 1876, commonly known as ‘Ich’ – the causative agent of white-spot disease. This protozoan was identified in several screened ornamental fishes including: swordtail *Xiphophorus helleri* Heckel, 1848, oscar, arawana *Osteoglossum bicirrhosum* Cuvier, 1829 and cardinal tetra *Paracheirodon axelrodi* Schultz, 1956. In addition, *Trichodina* Ehrenberg, 1838, another widespread protozoan genus already found in the UK, was identified as associated with several of the screened ornamental species. *Aphanomyces astaci* Schikora, 1906, which is widely distributed throughout Europe and the causative agent of the crayfish plague, was associated with the redclaw crayfish. Arthropoda PPPs, common in the UK, associated with listed species included *Argulus japonicus* Thiele, 1900 and *Argulus foliaceus* L., 1758.

However, PPPs not known to occur in UK waters were identified. For example, infection of fathead minnow by viral haemorrhagic septicaemia virus (VHSV), the aetiological agent of OIE-listed Viral Haemorrhagic Septicaemia, and of the oscar by infectious spleen and necrosis virus (ISKNV) were reported. In addition, the protist *Aphanomyces invadans* David & Kirk, 1997, the aetiological agent of OIE listed Epizootic Ulcerative Syndrome, was reported as associated with the rosy barb *Pethia conchonius* Hamilton, 1822. Further, the fungi *Pseudoloma neurophilia* was reported to cause mortality in the fathead minnow. Finally, the Cnidarian, *Myxobolus axelrodi*, was associated with the cardinal tetra and was also reported to cause mortalities.

Also identified were PPPs with zoonotic potential, including two trematodes, *Isthmiophora hortensis* Asata, 1926 and *Clinostomum complanatum* Rudolphi, 1814 were reported as associated with the dojo loach and rosy bitterling *Rhodeus ocellatus* Kner, 1868, respectively. One cestode, *Schyzocotyle acheilognathi* Yamaguti, 1934, also with known zoonotic potential, was reported as associated with swordtail. Bacterial PPPs known to infect both fishes and humans were also identified as associated with screened fishes, including: *Acinetobacter pittii* Nemec et al., 2011, *Aeromonas veronii* Hickman-Brenner et al., 1987, *A. hydrophila* Chester, 1901, *Vibrio cholerae* Pacini, 1854, *Shewanella putrefaciens* MacDonell & Colwell, 1986, *Mycobacterium marinum* Aronson, 1926 and *Mycobacterium goodii* Brown et al., 1999. Antimicrobial resistance was reported for some bacterial strains identified in screened species, including a strain of *Aeromonas sobria* Popoff & Vron, 1981 (in swordtail and dojo loach).



**Table 3.** List of potential pathogens and parasites reported as natural infections of ornamental fish and invertebrate species traded into the UK , whereby literature evidence was found (Y = Yes) for: Disease = clinical signs or disease in the animal caused by the associated pathogen or parasite; Mort. = mortalities in the animal as a result of the associated pathogen or parasite; Sub. = sub-clinical or asymptomatic infection in the animal. Location types: ‘Aquarium’ includes reports on specimens held in aquaria by hobbyists, public aquaria, vets or laboratories; ‘Retail (Pet shop)’ (Retail P) includes ornamental fish shops, both stand-alone and within ornamental markets; ‘Border’ refers to Import/Border Border Control Inspection Posts; ‘Retail B’ = Retail bait shop; ‘Retail S’ = Retail Spa.

Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
<b>Viruses</b>							
Aquatic birnavirus	<i>Garra rufa</i>		Y		Ireland	Retail S	(Ruane et al. 2013)
Athtabvirus	<i>Cherax quadricarinatus</i>	Y	Y		Australia	Farm	(Sakuna et al. 2018)
Chequa iflavirus	<i>Cherax quadricarinatus</i>	Y	Y	Y	Australia	Farm	(Sakuna, et al. 2017)
Cherax quadricarinatus iridovirus	<i>Cherax quadricarinatus</i>	Y	Y		China	Farm	(Xu et al. 2016)
Decapod ambidensovirus <sup>1</sup>	<i>Cherax quadricarinatus</i>	Y	Y		Australia	Farm	(Bochow et al. 2015)
Fathead minnow calicivirus	<i>Pimephales promelas</i>	Y		Y	USA	Retail B	(Mor et al. 2017)
Fathead minnow nidovirus	<i>Pimephales promelas</i>	Y		Y	USA	Retail B	(Batts et al. 2012)
Fathead minnow picornavirus	<i>Pimephales promelas</i>	Y			USA	Retail B	(Phelps et al. 2014)
Fathead minnow rhabdovirus	<i>Pimephales promelas</i>	Y	Y		USA	Farm	(Iwanowicz and Goodwin 2002)
Golden shiner reovirus	<i>Pimephales promelas</i>	Y		Y	USA	Retail B	(Boonthai et al. 2018)
Hepatopancreatic reovirus	<i>Cherax quadricarinatus</i>	Y	Y	Y	Australia	Farm	(Edgerton et al. 2000)
ISK necrosis virus	<i>Astronotus ocellatus</i>				Australia	Retail P	(Go et al. 2016)
ISK necrosis virus	<i>Astronotus ocellatus</i>			Y	India	Retail P	(Girisha et al. 2021)
Loach birnavirus	<i>Misgurnus anguillicaudatus</i>	Y			Taiwan	Farm	(Chou et al. 1993)
Parvo-like virus	<i>Cherax quadricarinatus</i>	Y	Y		Australia	Farm	(Bowater et al. 2002)
South American cichlid iridovirus	<i>Astronotus ocellatus</i>	Y	Y		USA	Retail P	(Koda et al. 2018)
Spawner-isolated mortality virus	<i>Cherax quadricarinatus</i>		Y	Y	Australia	Farm	(Owens and McElnea 2000)
Turbot reddish body iridovirus	<i>Astronotus ocellatus</i>				USA	Retail P	(Go et al. 2016)
Viral Haemorrhagic Septicaemia <sup>2</sup>	<i>Pimephales promelas</i>			Y	USA	Wild	(Cornwell et al. 2013)
<b>Bacteria</b>							
<i>Acinetobacter pittii</i>	<i>Misgurnus anguillicaudatus</i>	Y	Y		China	Farm	(Wang et al. 2019)
<i>Aeromonas hydrophila</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
<i>Aeromonas hydrophila</i>	<i>Misgurnus anguillicaudatus</i>	Y	Y		South Korea	Farm	(Jun et al. 2010)
<i>Aeromonas sobria</i>	<i>Corydoras paleatus</i>			Y	Italy	Wholesaler	(Sicuro et al. 2020)
<i>Aeromonas sobria</i>	<i>Garra rufa</i>	Y	Y		Slovakia	Farm	(Majtán et al. 2012)
<i>Aeromonas sobria</i>	<i>Misgurnus anguillicaudatus</i>			Y	Italy	Wholesaler	(Sicuro et al. 2020)
<i>Aeromonas sobria</i>	<i>Misgurnus mizolepis</i>	Y	Y		South Korea	Farm	(Yu et al. 2015)
<i>Aeromonas sobria</i>	<i>Xiphophorus hellerii</i>			Y	Italy	Wholesaler	(Sicuro et al. 2020)
<i>Aeromonas veronii</i>	<i>Astronotus ocellatus</i>	Y	Y		India	Farm	(Sreedharan et al. 2011)
<i>Aeromonas veronii</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)



Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
<b>Bacteria</b>							
<i>Chryseobacterium cucumeris</i>	<i>Misgurnus anguillicaudatus</i>	Y	Y		South Korea	Farm	(Kim et al. 2020)
<i>Citrobacter freundii</i>	<i>Garra rufa</i>	Y	Y		South Korea	Farm	(Baeck et al. 2009)
<i>Edwardsiella ictaluri</i>	<i>Pethia conchonius</i>	Y	Y	Y	Australia	Border	(Humphrey et al. 1986)
<i>Listonella anguillarum</i>	<i>Misgurnus anguillicaudatus</i>	Y	Y		China	Farm	(Qin et al. 2014)
<i>Mycobacterium abscessus</i>	<i>Xiphophorus variatus</i>	Y	Y		Italy	Border	(Zanoni et al. 2008)
<i>Mycobacterium fortuitum</i>	<i>Xiphophorus variatus</i>	Y	Y		Italy	Aquarium	(Zanoni et al. 2008)
<i>Mycobacterium goodii</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
<i>Mycobacterium gordonae</i>	<i>Cherax quadricarinatus</i>	Y	Y		Israel	Farm	(Davidovich et al. 2019)
<i>Mycobacterium marinum</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
Rickettsia-like organism	<i>Cherax quadricarinatus</i>	Y	Y		Ecuador	Farm	(Romero et al. 2000)
<i>Shewanella putrefaciens</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
<i>Shewanella putrefaciens</i>	<i>Misgurnus anguillicaudatus</i>	Y	Y		China	Farm	(Qin et al. 2014)
<i>Streptococcus agalactiae</i>	<i>Garra rufa</i>	Y	Y		Ireland	Retail S	(Ruane et al. 2013)
<i>Streptococcus iniae</i>	<i>Astronotus ocellatus</i>	Y			Iran	Aquarium	(Tukmechi et al. 2009)
<i>Vibrio cholerae</i>	<i>Garra rufa</i>	Y	Y	Y	Italy	Retail S	(Volpe et al. 2019)
<b>Protists</b>							
<i>Achlya</i> sp.	<i>Astronotus ocellatus</i>	Y			Iran	Aquarium	(Peyghan et al. 2019)
<i>Aphanomyces astaci</i>	<i>Cherax quadricarinatus</i>	Y	Y		Taiwan	Farm	(Hsieh et al. 2016)
<i>Aphanomyces invadans</i>	<i>Pethia conchonius</i>	Y	Y		India	Wild	(Pradhan et al. 2014)
<i>Dermocystidium salmonis</i>	<i>Paracheirodon axelrodi</i>	Y	Y		Germany	Aquarium	(Langenmayer et al. 2015)
<i>Ichthyobodo necator</i>	<i>Xiphophorus hellerii</i>				USA		(Callahan et al. 2005)
<i>Ichthyophthirius multifiliis</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
<i>Ichthyophthirius multifiliis</i>	<i>Osteoglossum bicirrhosum</i>				Brazil	Wild	(Rodrigues et al. 2014)
<i>Ichthyophthirius multifiliis</i>	<i>Paracheirodon axelrodi</i>				Brazil	Retail P	(Hoshino et al. 2018)
<i>Ichthyophthirius multifiliis</i>	<i>Xiphophorus hellerii</i>				Australia	Wild	(Dove and Ernst 1998)
<i>Piscinoodinium pillulare</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
<i>Piscinoodinium pillulare</i>	<i>Osteoglossum bicirrhosum</i>				Brazil	Wild	(Rodrigues et al. 2014)
<i>Tokophrya huangmeiensis</i>	<i>Cherax quadricarinatus</i>				China	Farm	(Tahir et al. 2017)
<i>Trichodina acuta</i>	<i>Misgurnus anguillicaudatus</i>				China	Farm	(Wang et al. 2017)
<i>Trichodina acuta</i>	<i>Xiphophorus hellerii</i>				Brazil	Farm	(Piazza et al. 2006; Garcia et al. 2009)
<i>Trichodina heterodontata</i>	<i>Xiphophorus hellerii</i>				Australia	Wild	(Dove 2000)
<i>Trichodina lechriodontata</i>	<i>Misgurnus anguillicaudatus</i>				China		(Zhao and Tang 2007)
<i>Trichodina modesta</i>	<i>Misgurnus anguillicaudatus</i>				China		(Zhao and Tang 2007)
<i>Trichodina</i> sp.	<i>Paracheirodon axelrodi</i>				Brazil	Wild	(Tavares-Dias et al. 2010)
<i>Trichodina</i> sp.	<i>Pimephales promelas</i>				USA	Wild	(Weichman and Janovy 2000)
<i>Trichodina</i> sp.	<i>Xiphophorus hellerii</i>				Sri Lanka	Farm	(Thilakaratne et al.
<b>Fungi</b>							
<i>Apotasporea heleios</i>	<i>Palaemonetes paludosus</i>	Y			USA	Wild	(Sokolova and Overstreet 2018)
<i>Exophiala pisciphila</i>	<i>Paracheirodon axelrodi</i>	Y			Czechia	Aquarium	(Rehulka et al. 2017)
<i>Glugea pimephales</i>	<i>Pimephales promelas</i>	Y			Canada	Wild	(Forest, et al. 2009)
<i>Pleistophora hyphessobryconis</i>	<i>Paracheirodon axelrodi</i>				Czechia	Aquarium	(Novotný and Dvořák 2001)
<i>Pleistophora</i> sp.	<i>Pimephales promelas</i>			Y	USA	Farm	(Ruehl-Fehlert et al. 2005)



Type & name of Disease Agent	Ornamental Species	Disease	Mort.	Sub.	Country	Location type	Reference
<b>Fungi</b>							
<i>Pseudoloma neurophilia</i>	<i>Pimephales promelas</i>	Y	Y		UK	Aquarium	(Sanders et al. 2016)
<b>Animal Kingdom</b>							
Acanthocephala							
<i>Acanthocephalan polymorphus</i> sp.	<i>Astronotus ocellatus</i>				Brazil	Wild	(Azevedo et al. 2007)
<i>Neoechinorhynchus panucensis</i>	<i>Amatitlania nigrofasciata</i>				Mexico	Wild	(Salgado-Maldonado 2013)
<i>Triaspiroa aphanii</i>	<i>Aphanius mento</i>				Turkey	Wild	(Smales et al. 2012)
Annelida							
<i>Chaetogaster limnaei</i> sp.	<i>Tarebia granifera</i>				Jamaica	Wild	(McKoy et al. 2011)
	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013)
<i>Glossiphoniidae</i> gen. sp.	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013)
Arthropoda							
<i>Argulus foliaceus</i>	<i>Astronotus ocellatus</i>				Turkey		(Toksen 2006)
<i>Argulus japonicus</i>	<i>Rhodeus ocellatus</i>				Japan	Wild	(Yamauchi and Shimizu 2013)
<i>Argulus multicolor</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Tavares-Dias and Neves 2017)
<i>Dolops nana</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013)
<i>Ergasilus ceylonensis</i>	<i>Xiphophorus hellerii</i>				Sri Lanka	Farm	(Thilakaratne et al. 2003)
<i>Lamproglana monodi</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Azevedo et al. 2012)
<i>Lernaea cyprinacea</i>	<i>Corydoras paleatus</i>				Argentina	Wild	(Paul et al. 2010)
<i>Lernaea cyprinacea</i>	<i>Pimephales promelas</i>				USA	Wild	(Marcogliese 1991)
<i>Lernaea cyprinacea</i>	<i>Rhodeus ocellatus</i>				Japan	Wild	(Nagasawa and Torii 2014)
<i>Lernaea cyprinacea</i>	<i>Xiphophorus hellerii</i>				Iran	Farm	(Mirzaei 2015)
<i>Neoergasilus japonicus</i>	<i>Pimephales promelas</i>				USA	Wild	(Hudson and Bowen 2002)
<i>Probopyrus pandalicola</i>	<i>Palaemonetes paludosus</i>				USA	Wild	(Beck 1980)
<i>Sebekia mississippiensis</i>	<i>Xiphophorus helleri</i>				USA	Retail P	(Boyce et al. 1987)
Cnidaria							
<i>Myxobolus axelrodi</i>	<i>Paracheirodon axelrodi</i>		Y				(Camus et al. 2017)
<i>Thelohanellus misgurni</i>	<i>Misgurnus mizolepis</i>						(Kwon and Kim 2011)
Nematoda							
<i>Anguillicoloides crassus</i>	<i>Amatitlania nigrofasciata</i>				Germany	Wild	(Emde et al. 2016)
<i>Camallanus acaudatus</i>	<i>Osteoglossum bicirrhosum</i>				Brazil	Wild	(Rodrigues et al. 2014)
<i>Camallanus cotti</i>	<i>Amatitlania nigrofasciata</i>				Germany	Wild	(Emde et al. 2016)
<i>Camallanus cotti</i>	<i>Misgurnus anguillicaudatus</i>				Canada	Aquarium	(Moravec and Justine 2006)
<i>Camallanus cotti</i>	<i>Xiphophorus hellerii</i>				USA	Wild	(Vincent and Font 2003)
<i>Camallanus</i> sp.	<i>Paracheirodon axelrodi</i>				Brazil	Retail P	(Hoshino et al. 2018)
<i>Contracaecum bancrofti</i>	<i>Misgurnus anguillicaudatus</i>				Australia	Wild	(Shamsi et al. 2019)
<i>Contracaecum</i> sp.	<i>Astronotus ocellatus</i>				Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)
<i>Contracaecum</i> sp.	<i>Osteoglossum bicirrhosum</i>				Brazil	Wild	(Oliveira et al. 2019)
<i>Contracaecum</i> sp.	<i>Pimephales promelas</i>				USA	Wild	(Martins et al. 2017)
<i>Eustrongylides excisus</i>	<i>Aphanius mento</i>				Turkey	Wild	(Aydo_du et al. 2011)
<i>Eustrongylides</i> sp.	<i>Osteoglossum bicirrhosum</i>				Brazil	Wild	(Oliveira et al. 2019)
<i>Gnathostoma nipponicum</i>	<i>Misgurnus anguillicaudatus</i>				South Korea	Retail P	(Sohn et al. 1993)
<i>Mexiconema cichlasomae</i>	<i>Xiphophorus hellerii</i>				Mexico	Wild	(Moravec et al. 1998)
<i>Procamallanus inopinatus</i>	<i>Astronotus ocellatus</i>				Brazil	Wild	(Tavares-Dias, Sousa and Neves 2014)
<i>Procamallanus pintoii</i>	<i>Corydoras paleatus</i>				Argentina	Wild	(Ailán-Choke et al. 2018)
<i>Procamallanus</i> sp.	<i>Paracheirodon axelrodi</i>				Brazil	Wild	(Tavares-Dias et al. 2010)



Type & name of Disease Agent	Ornamental Species	Disease Mort.	Sub.	Country	Location type	Reference
Nematoda						
<i>Procamallanus spiculastratus</i>	<i>Astronotus ocellatus</i>			Brazil	Wild	(Pinheiro et al.2019)
<i>Pseudocapillaria margolisi</i>	<i>Pethia conchoniui</i>			India	Wild	(De and Maity 1996)
<i>Pseudoproleptus</i> sp.	<i>Astronotus ocellatus</i>			Brazil	Wild	(Pinheiro et al. 2019)
Platyhelminthes						
<i>Acanthatrium hitaense</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Dechruska and Krailas 2007)
<i>Acanthostomum</i> sp.	<i>Paracheirodon axelrodi</i>			Brazil	Retail P	(Hoshino et al. 2018)
<i>Caballerotrema aruanense</i>	<i>Osteoglossum bicirrhosum</i>			Brazil	Wild	(Oliveira et al. 2019)
<i>Centrocestus formosanus</i>	<i>Barbodes semifasciolatus</i>			Vietnam	Wild	(Chai et al.2012)
<i>Centrocestus formosanus</i>	<i>Melanoides tuberculata</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)
<i>Centrocestus formosanus</i>	<i>Osteoglossum bicirrhosum</i>			Iran	Wild	(Mood et al. 2010)
<i>Centrocestus formosanus</i>	<i>Tarebia granifera</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)
<i>Centrocestus formosanus</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Dechruska and Krailas 2007)
<i>Clinostomum complanatum</i>	<i>Misgurnus anguillicaudatus</i>			Taiwan	Farm	(Wang et al. 2017)
<i>Clinostomum complanatum</i>	<i>Rhodeus ocellatus</i>			Japan	Wild	(Aohagi et al. 1992)
<i>Clinostomum marginatum</i>	<i>Astronotus ocellatus</i>			Brazil	Wild	(Tavares-Dias and Neves 2017)
<i>Clonorchis sinensis</i>	<i>Misgurnus anguillicaudatus</i>			China	Wild	(Zhang et al. 2014)
<i>Clonorchis sinensis</i>	<i>Misgurnus anguillicaudatus</i>			South Korea	Wild	(Shin 1964)
<i>Clonorchis sinensis</i>	<i>Rhodeus ocellatus</i>			South Korea	Wild	(Rhee et al. 1983)
<i>Craspedella pedum</i>	<i>Cherax quadricarinatus</i>			South Africa	Wild	(Tavakol et al. 2016)
<i>Crassiphiala bulboglossa</i>	<i>Pimephales promelas</i>			USA	Wild	(Wisenden et al. 2012)
<i>Dactylogyrus olfactorius</i>	<i>Pimephales promelas</i>			USA	Wild	(Lari et al. 2016)
<i>Dactylogyrus simplex</i>	<i>Pimephales promelas</i>			USA	Wild	(Knipes and Janovy 2009)
<i>Dactylogyrus bychowskyi</i>	<i>Pimephales promelas</i>			USA	Wild	(Knipes and Janovy 2009)
<i>Dactylogyrus pectenatus</i>	<i>Pimephales promelas</i>			USA	Wild	(Knipes and Janovy 2009)
<i>Dactylogyrus ostraviensis</i>	<i>Pethia conchoniui</i>		Y	Australia	Border	(Trujillo-González et al. 2019)
<i>Dactylogyrus</i> sp.	<i>Garra rufa</i>			Iraq	Wild	(Abdullah 2017)
<i>Dactylogyrus</i> sp.	<i>Xiphophorus hellerii</i>			Sri Lanka	Farm	(Thilakaratne et al. 2003)
<i>Diceratocephala boschmai</i>	<i>Cherax quadricarinatus</i>			Thailand	Wild	(Ngamniyom et al. 2019)
<i>Diceratocephala boschmai</i>	<i>Cherax quadricarinatus</i>			South Africa	Wild	(Tavakol et al. 2016)
<i>Didymorchis</i> sp.	<i>Cherax quadricarinatus</i>			South Africa	Wild	(Tavakol et al. 2016)
Diplostomidae sp.	<i>Paracheirodon axelrodi</i>			Brazil	Retail P	(Hoshino et al. 2018)
<i>Echinostoma cinetorchis</i>	<i>Misgurnus anguillicaudatus</i>			South Korea	Retail P	(Seo et al. 1984)
<i>Echinostoma</i> sp.	<i>Melanoides tuberculata</i>			Philippines	Wild	(Paller et al. 2019)
<i>Gonocleithrum aruanae</i>	<i>Osteoglossum bicirrhosum</i>			Brazil	Wild	(Tavares-Dias et al. 2014)
<i>Gonocleithrum coenoideum</i>	<i>Osteoglossum bicirrhosum</i>			Brazil	Wild	(Rodrigues et al. 2014)
<i>Gonocleithrum cursitans</i>	<i>Osteoglossum bicirrhosum</i>			Iran	Retail P	(Mehdizadeh et al. 2016)
<i>Gonocleithrum planacrus</i>	<i>Osteoglossum bicirrhosum</i>			Brazil	Wild	(Rodrigues et al. 2014)
<i>Gussevia asota</i>	<i>Astronotus ocellatus</i>			Peru	Wild	(Mendoza-Franco et al. 2010)
<i>Gussevia asota</i>	<i>Astronotus ocellatus</i>			Panama	Wild	(Mendoza-Franco et al. 2007)
<i>Gussevia asota</i>	<i>Astronotus ocellatus</i>			South Korea	Farm	(Kim et al. 2002)
<i>Gussevia astronii</i>	<i>Astronotus ocellatus</i>			Brazil	Wild	(Neves et al. 2013; Tavares-Dias and Neves 2017)



Type & name of Disease Agent	Ornamental Species	Disease Mort.	Sub.	Country	Location type	Reference
Nematoda						
<i>Gussevnia rogersi</i>	<i>Astronotus ocellatus</i>			Brazil	Wild	(Neves et al. 2013)
<i>Gyrodactylus anisopharynx</i>	<i>Corydoras paleatus</i>			Argentina	Wild	(Rauque et al. 2018)
<i>Gyrodactylus anisopharynx</i>	<i>Corydoras paleatus</i>			Brazil	Wild	(Boeger et al. 2005) <sup>3</sup>
<i>Gyrodactylus bullatarudis</i>	<i>Xiphophorus hellerii</i>			Australia	Wild	(Dove and Ernst 1998)
<i>Gyrodactylus cichlidarum</i>	<i>Astronotus ocellatus</i>			Iran	Retail P	(Mousavi et al. 2013)
<i>Gyrodactylus corydori</i>	<i>Corydoras paleatus</i>			Brazil	Wild	(Bueno-silva et al. and Boeger 2009)
<i>Gyrodactylus macracanthus</i>	<i>Misgurnus anguillicaudatus</i>			Australia	Wild	(Dove and Ernst 1998)
<i>Gyrodactylus medaka</i>	<i>Oryzias latipes</i>			Japan	Wild	(Nitta and Nagasawa 2018)
<i>Gyrodactylus samirae</i>	<i>Corydoras paleatus</i>			Brazil	Wild	(Popazoglo and Boeger 2016)
<i>Gyrodactylus</i> sp.	<i>Misgurnus anguillicaudatus</i>			USA	Wild	(Reyda et al. 2020)
<i>Gyrodactylus</i> sp.	<i>Paracheirodon axelrodi</i>			Brazil	Wild	(Tavares-Dias et al. 2010)
<i>Gyrodactylus</i> sp.	<i>Xiphophorus hellerii</i>			Sri Lanka	Farm	(Thilakaratne et al. 2003)
<i>Gyrodactylus superbis</i>	<i>Corydoras paleatus</i>			Argentina	Wild	(Rauque et al. 2018)
<i>Haematoloechus similis</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Dechruska and Krailas 2007)
<i>Haplorchis pumilio</i>	<i>Barbodes semifasciolatus</i>			Vietnam	Wild	(Chai et al. 2012)
<i>Haplorchis pumilio</i>	<i>Melanoides tuberculata</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)
<i>Haplorchis pumilio</i>	<i>Melanoides tuberculata</i>			Thailand	Wild	(Dechruska and Krailas 2007)
<i>Haplorchis pumilio</i>	<i>Tarebia granifera</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)
<i>Haplorchis</i> sp.	<i>Tarebia granifera</i>			Laos	Wild	(Ditrich et al. 1990)
<i>Haplorchis taichui</i>	<i>Melanoides tuberculata</i>			Thailand	Wild	(Chontanarith and Wongsawad 2010)
<i>Haplorchis taichui</i>	<i>Melanoides tuberculata</i>			Laos	Wild	(Nawa et al. 2001)
<i>Haplorchis taichui</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Chontanarith and Wongsawad 2010)
<i>Haplorchis taichui</i>	<i>Tarebia granifera</i>			Laos	Wild	(Nawa et al. 2001)
<i>Herpetodiplostomum</i> sp.	<i>Astronotus ocellatus</i>			Brazil	Wild	(Neves et al. 2013)
<i>Isthmiophora hortensis</i> <sup>4</sup>	<i>Misgurnus anguillicaudatus</i>			China	Wild	(Qiu et al. 2017)
<i>Isthmiophora hortensis</i> <sup>4</sup>	<i>Misgurnus anguillicaudatus</i>			South Korea	Wild	(Ryang 1990)
<i>Isthmiophora hortensis</i> <sup>4</sup>	<i>Misgurnus anguillicaudatus</i>			South Korea	Retail P	(Jong-Yil Chai et al. 1985)
<i>Loxogenoides bicolor</i>	<i>Melanoides tuberculata</i>			Thailand	Wild	(Ukong et al. 2007)
<i>Loxogenoides bicolor</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Ukong et al. 2007)
<i>Massaliatrema misgurni</i>	<i>Misgurnus anguillicaudatus</i>			Japan	Retail P	(Ohyama et al. 2001)
<i>Megulurous</i> sp.	<i>Melanoides tuberculata</i>			Philippines	Wild	(Paller et al. 2019)
<i>Metorchis orientalis</i>	<i>Rhodeus ocellatus</i>			China	Wild	(Qiu et al. 2017)
Notocotylid sp.	<i>Tarebia granifera</i>			Jamaica	Wild	(McKoy et al. 2011)
<i>Ornithodiplostomum ptychocheilus</i>	<i>Pimephales promelas</i>			USA	Wild	(Wisenden et al. 2012)
<i>Ornithodiplostomum ptychocheilus</i>	<i>Pimephales promelas</i>			Canada	Wild	(Sandland and Goater 2001; Sandland et al. 2001) <sup>5</sup>
<i>Paracaryophyllaeus gotoi</i>	<i>Misgurnus anguillicaudatus</i>			Japan	Wild	(Scholz et al. 2001)
<i>Parapleurophocercous</i> sp.	<i>Melanoides tuberculata</i>			Philippines	Wild	(Paller et al. 2019)
<i>Parapleurophocercous</i> sp.	<i>Tarebia granifera</i>			Philippines	Wild	(Paller et al. 2019)
<i>Philophthalmus gralli</i>	<i>Melanoides tuberculata</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)



Type & name of Disease Agent	Ornamental Species	Disease Mort.	Sub.	Country	Location type	Reference
Nematoda						
<i>Philophthalmus gralli</i>	<i>Tarebia granifera</i>			USA	Wild	(Tolley-Jordan and Chadwick 2018)
<i>Philophthalmus</i> sp.	<i>Tarebia granifera</i>			Jamaica	Wild	(McKoy et al. 2011)
<i>Posthodiplostomum minimum</i>	<i>Pimephales promelas</i>			Canada	Wild	(Schleppe and Goater 2004)
<i>Posthodiplostomum minimum</i>	<i>Pimephales promelas</i>			USA	Farm	(Mitchell et al. 1982)
<i>Posthodiplostomum</i> sp.	<i>Astronotus ocellatus</i>			Brazil	Wild	(Neves et al. 2013) <sup>6</sup>
<i>Pimephales promelas</i>	<i>Posthodiplostomum</i> sp.			USA	Wild	(Weichman and Janovy 2000)
<i>Proteocephalus gibsoni</i>	<i>Astronotus ocellatus</i>			Brazil	Wild	(Tavares-Dias and Neves 2017)
<i>Proteocephalus misgurni</i>	<i>Misgurnus anguillicaudatus</i>			Russia	Wild	(Scholz et al. 2014)
<i>Prototransversotrema steeri</i>	<i>Xiphophorus hellerii</i>			Sri Lanka	Farm	(Dove 2000)
<i>Pseudolevinseniella anenteron</i>	<i>Cherax quadricarinatus</i>			Thailand	Wild	(Ngamniyom et al. 2019)
<i>Paradiplozoon bingolensis</i>	<i>Garra rufa</i>			Turkey	Wild	(Civanova et al. 2013)
<i>Schyzocotyle acheilognathi</i>	<i>Pimephales promelas</i>			USA	Retail B	(Boonthai et al. 2017)
<i>Schyzocotyle acheilognathi</i>	<i>Xiphophorus hellerii</i>			USA	Wild	(Vincent and Font 2003)
<i>Stellantchasmus falcatus</i>	<i>Tarebia granifera</i>			Thailand	Wild	(Chontanarith et al. 2018)
<i>Temnosewellia</i> sp.	<i>Cherax quadricarinatus</i>			Thailand	Wild	(Ngamniyom et al. 2019)
<i>Tetracotyle wayanadensis</i>	<i>Pethia conchonius</i>			India	Wild	(Jithila and Prasadani 2018)
<i>Thometrema</i> sp.	<i>Astronotus ocellatus</i>			Brazil	Wild	(Tavares-Dias and Neves 2017)
<i>Uvulifer ambloplitis</i>	<i>Pimephales promelas</i>			USA	Wild	(Weichman and Janovy 2000)
<i>Telethecium nasalis</i>	<i>Osteoglossum bicirrhosum</i>			Brazil	Wild	(Kritsky et al. 1996)

<sup>1</sup>variant *Cherax quadricarinatus densovirus*; <sup>2</sup>Rhabdovirus; <sup>3</sup>Also Pie and Boeger (2006) and Bueno-silva and Boeger (2009); <sup>4</sup>Also Reported under synonym *Echinostoma hortense* ; <sup>5</sup> Aso Schleppe and Goater (2004); <sup>6</sup> Also Tavares-Dias and Neves (2017) and Pinheiro et al. (2019).

Discussion

Trade in live aquatic ornamental species is vast, benefitting from globalisation and improved transport in recent decades. Over 140 countries are involved in the international trade of more than 1500 fish and 300 aquatic invertebrate species (Weir et al. 2012; Hood et al. 2019). Our study provides an assessment of freshwater ornamental trade in the UK in which commonly traded species and their likelihood of establishment in UK waters under current and future climate conditions, with their potential pathogens and parasites also identified..

These data on commonly traded species are a snapshot in time, which potentially limits accuracy and prevents the assessment of seasonal and annual variations. That said, the six species identified were listed amongst the 30 species reported to predominate the global trade in ornamental freshwater organisms in a relatively recent review: Endler’s livebearer, goldfish, zebra danio, neon tetra *Paracheirodon innesi* Myers, 1936, angel fish *Pterophyllum scalare* Schultze, 1823, and discus *Symphysodon aequifasciatus* Pellegrin, 1904 (Dey 2016).

Access to robust ornamental trade data, in particular with respect to species traded and import origin, is fundamental to fill knowledge gaps and inform risk screenings and the risk analysis process (Copp et al. 2016; Chan et al. 2019). A comprehensive understanding of spatial and temporal trade patterns to species level will increase capacity to



identify high risk links, facilitating targeted and cost-effective surveillance. Species-level information will also support analyses from a conservation point of view, particularly for marine species that are wild sourced, and ensure there is increased transparency in the source, quantity and sustainability of trade for each species (Andersson et al. 2021). In the UK, aquatic species imports from third party countries are electronically recorded on the ‘Import of Animals Food and Feed System’ (IPAFFS). Historically, non-susceptible aquatic species imported from the EU for ornamental use were not recorded on any system. As of January 2021, all aquatic imports must be recorded on IPAFFS, but records on this database are categorised by international commodity codes ([www.uktradeinfo.com/find-commodity-data/help-with-classifying-goods/](http://www.uktradeinfo.com/find-commodity-data/help-with-classifying-goods/)). However, the purpose of these codes is to enable the application of appropriate tariffs to imported goods and they do not provide sufficient resolution to identify consignments to species level, so cannot be used to inform disease susceptibility or invasive potential. Import data at the species-level for the UK currently exist in paper format only (on the invoices that accompany all other relevant import certification), though there are periods for which species-level electronic data have been available for freshwater fishes, including ornamental varieties, imported to England between 2000 and 2004 inclusive (see Copp et al. 2007). Limitations with respect to access to detailed live ornamental import data are not unique to the UK (Rhyne et al. 2012, 2017; Leal et al. 2016; Pinnegar and Murray 2019; Biondo and Burki 2020). Creation of an import data App, or extension of an existing, established App, is an opportunity to capture detailed import data, integrating species trade information with other crucial information such as invasiveness potential, associated disease threats and conservation status. Such a system would enhance capacity for real-time monitoring and analysis, at the point of exporter application for import, allowing trade in high risk species to be tracked and incidences of illicit trade, such as the import of prohibited species, to be detected in a timely manner (Rhyne et al. 2017).

Legislative instruments restrict the keeping of many temperate species but do allow the keeping of numerous commonly traded tropical and sub-tropical species. The application of SDMs indicated that, while establishment of commonly traded species if released into the wild is unlikely in the UK under current conditions, predicted temperature increases associated with climate change may increase risks of survival and establishment. The mean increase in temperature suitability of 2.4% and 1.8% for fish and invertebrates, respectively, by 2050 under RCP 4.5 demonstrated in our study may seem a small increase in ‘risk’, but RCP 4.5 represents a moderate climate-change scenario, and temperature increases may be greater than this scenario predicts. Although a broad scale indication of the change in suitability under climate change is provided, careful interpretation of SDM outputs may be required. For instance, the red shiner *Cyprinella lutrensis* Baird & Girard, 1853, is widespread across the USA and has been identified, using the Fish Invasiveness Screening Kit, as posing a medium risk of being invasive in England and Wales (Copp et al. 2009). However, the red shiner had a relatively low suitability score (0.10) under current day conditions in our study (Table 2). The Chinese muddy loach *Misgurnus mizolepis* Guenther, 1888 had a suitability score of 0.26 under current day conditions, yet there has been only one record of a reproducing population in the UK (in southern England), which was subsequently eradicated (Zięba et al. 2010).



Although outside the scope of our study, there will be value in assessing species suitability at a finer spatial resolution, for example accounting for differences in conditions across the entirety of the UK (Thrush and Peeler 2013), for example, the notably warmer conditions in the South compared to the North UK, affecting the risks of survival and establishment of sub-tropical and tropical species (see Suppl. material 1: Figs S1, S2). Further, extension of the SDMs to incorporate environmental factors such as rainfall, habitat type or elevation (Logez et al. 2012), species' life-history traits such as size or fecundity (Copp and Fox 2007; Liu and Olden 2017), and consideration of the likelihood of release of each species (i.e. potential propagule pressure) will be of value. For example, inclusion of elevation will account for species with native distributions at higher altitudes within the tropical zone that may be more adapted to temperature conditions more similar to the temperate zone species due to Rapoport's latitudinal rule to altitude (Stevens 1992).

In total, 155 PPPs were found to be associated with the screened ornamental fishes and invertebrates. Despite following a standardised approach for each host species, the number of PPPs identified in the literature may be skewed by the research effort applied to a species and affected by the use of different accepted names or synonyms. One of the key drivers of impacts associated with NN aquatic species (Peeler et al. 2011) are PPPs, with disease emergence events resulting from NNS introductions being well documented (Taraschewski 2006; Peeler et al. 2011; Lymbery et al. 2014). Disease emergence can be driven solely by a switch in geographical range, because a new environment may favour increased PPP virulence, or by host switching and pathogen/parasite spillover (Peeler et al. 2011; Foster et al. 2021). Thermal tolerances of a PPP may also determine the likelihood and impact of disease emergence resulting from co-transportation, particularly for PPPs that can survive outside a host or have free-living stages (Barber et al. 2016).

Even if the long-term survival of an ornamental species is not supported by future UK temperatures, the host species may persist long enough to transmit a PPP to a native susceptible host or introduce a free-living stage which can survive. Temperature may also determine the likelihood of PPPs causing disease and morbidity in infected hosts. For example, KHV is thought to only cause clinical signs and mortality between 16 °C and 25 °C (OIE 2019), whereas outbreaks of VHS rarely occur above 15 °C (Baillon et al. 2020). While beyond the scope of this study there will be value in building on the present study by examining the environmental tolerances of the PPPs and the likely impact of climate change. Indeed, PPPs introduced via the ornamental pathway may cause wider impact, for example causing mortality and yield loss in aquaculture systems and affecting human health, although strong biosecurity and health and safety precautions can mitigate against such risks.

The PPPs that cause mortalities or clinical expression of disease in the traded host species are more likely to be detected via visual inspection or quarantine at border control posts or other stages in the ornamental trade pathway (Table 3). However, PPPs that live symbiotically with a host, or those PPPs that have sub-clinical or latent infection stages, provide a greater challenge to detection (Gomez et al. 2006; Becker et al. 2014). Traditionally, the testing of host species for PPP presence often requires destructive sampling, which limits the number of specimens and ultimately reduces the probability of PPP detection. However, new methodologies that incorporate molecular techniques



at border control posts, such as environmental DNA, may present a good non-lethal option (Trujillo-González et al. 2019b; Brunner 2020) for improved PPP detection. Measures such as heat ramping (gradually increasing the water temperature over a minimum period) can be used during quarantine to detect latent infections (Eide et al. 2011); however, this may not be appropriate for all PPPs, when surveillance aims to target multiple PPPs and where there is a need to adhere to animal welfare laws and guidance.

Though the remit of our study was to undertake a high-level screening to identify all PPPs associated with commonly traded ornamental species, rather than novel threats *per se*, we note that while some of the identified PPPs are known in the UK, others are not. Some PPPs are already known within the ornamental fish trade industry, and do not cause widespread impact or can be successfully treated to minimise impact. However, the abundance and diversity of PPPs increases potential for future disease outbreaks under changing environmental conditions. Even where a PPP has not yet been implicated in any mortality events, the changing climate and alterations to host communities (e.g. due to species introductions) may provide the perfect storm for disease emergence into the future. Next steps should aim to assess the risk associated with each PPP, focussing on the interplay between the PPP, all potential hosts and changing environmental conditions.

In conclusion, the ornamental fish trade is largely free from serious and untreatable diseases. However, through screening of a small subset of ornamental freshwater species, our study highlights the abundance and diversity of PPPs present in ornamental species commonly traded in the UK. An understanding of hazards associated with PPPs, in particular under changing ecological and environmental conditions, is crucial to determine and communicate risks and enhance risk awareness amongst stakeholders and the general public, thereby enabling mitigation through management actions (Britton et al. 2011) to ensure a safe and sustainable ornamental aquatics industry into the future (Copp et al. 2016).

## Acknowledgements

This work was funded by Department for Environment, Food & Rural Affairs, Project FB002. We would also like to express our gratitude to Alasdair Scott and anonymous reviewers for their helpful advice and comments on the manuscript.

## References

- Abdullah SMA (2017) First record of *Dactylogyrus rectotrabus* (Monogenetic Trematoda) from *Garra rufa* from Greater Zab River, North of Iraq, regarding its ecological aspects. Egypt Journal of Aquatic Biology and Fish 11: 1029–1040.
- Ailán-Choke LG, Ramallo G, Davies D (2018) Further study on *Procamallanus* (*Spirocamallanus*) *pinto* (Kohn et Fernandes, 1988) (Nematoda: Camallanidae) in *Corydoras paleatus* and *Corydoras micracanthus* (Siluriformes: Callichthyidae) from Salta, Argentina, with a key to congeneric species. Acta Parasitologica 63(3): 595–604. <https://doi.org/10.1515/ap-2018-0068>



- Andersson AA, Tilley HB, Lau W, Dudgeon D, Bonebrake TC, Dingle C (2021) CITES and beyond: Illuminating 20 years of global, legal wildlife trade. *Global Ecology and Conservation* 26: e01455. <https://doi.org/10.1016/j.gecco.2021.e01455>
- Aohagi Y, Shibahara T, Machida N, Yamaga Y, Kagota K (1992) *Clinostomum complanatum* (Trematoda: Clinostomatidae) in five new fish hosts in Japan. *Journal of Wildlife Diseases* 28(3): 467–469. <https://doi.org/10.7589/0090-3558-28.3.467>
- Baeck GW, Kim JH, Choresca C, Gomez DK, Shin SP, Han JE, Park SC (2009) Mass mortality of doctor fish (*Garra rufa obtusa*) caused by *Citrobacter freundii* infection. *Journal of Veterinary Clinics* 26: 150–154. <https://www.koreascience.or.kr/article/JAKO200916762902489.pdf>
- Baillon L, Mérour E, Cabon J, Louboutin L, Vigouroux E, Alencar ALF, Cuenca A, Blanchard Y, Olesen NJ, Panzarin V, Morin T, Brémont M, Biacchesi S (2020) The Viral Hemorrhagic Septicemia Virus (VHSV) markers of virulence in rainbow trout (*Oncorhynchus mykiss*). *Frontiers in Microbiology* 11: 1–17. <https://doi.org/10.3389/fmicb.2020.574231>
- Barber I, Berkhout BW, Ismail Z (2016) Thermal change and the dynamics of multi-host parasite life cycles in aquatic ecosystems. *Integrative and Comparative Biology* 56(4): 561–572. <https://doi.org/10.1093/icb/icw025>
- Barbet-Massin M, Jiguet F, Albert CH, Thuiller W (2012) Selecting pseudo-absences for species distribution models: How, where and how many? *Methods in Ecology and Evolution* 3(2): 327–338. <https://doi.org/10.1111/j.2041-210X.2011.00172.x>
- Batts WN, Goodwin AE, Winton JR (2012) Genetic analysis of a novel nidovirus from fat-head minnows. *Journal of General Virology* 93(6): 1247–1252. <https://doi.org/10.1099/vir.0.041210-0>
- Beck JT (1980) Life history relationships between the bopyrid isopod *Probopyrus pandalicola* and of its freshwater shrimp hosts *Palaemonetes paludosus*. *American Midland Naturalist* 104(1): 135–154. <https://doi.org/10.2307/2424966>
- Becker JA, Tweedie A, Rimmer A, Landos M, Lintermans M, Whittington RJ (2014) Incursions of Cyprinid herpesvirus 2 in goldfish populations in Australia despite quarantine practices. *Aquaculture (Amsterdam, Netherlands)* 432: 53–59. <https://doi.org/10.1016/j.aquaculture.2014.04.020>
- Biondo MV, Burki RP (2020) A systematic review of the ornamental fish trade with emphasis on coral reef fishes-An impossible task. *Animals (Basel)* 10(11): 1–21. <https://doi.org/10.3390/ani10112014>
- Bochow S, Condon K, Elliman J, Owens L (2015) First complete genome of an Ambidensovirus; *Cherax quadricarinatus* densovirus, from freshwater crayfish *Cherax quadricarinatus*. *Marine Genomics* 24: 305–312. <https://doi.org/10.1016/j.margen.2015.07.009>
- Boeger WA, Kritsky D, Pie MR, Engers KB (2005) Mode of transmission, host switching, and escape from the red queen by viviparous gyrodactylids (Monogeneoidea). *The Journal of Parasitology* 9(5): 1000–1007. <https://doi.org/10.1645/GE-515R.1>
- Boonthai T, Herbst SJ, Whelan GE, Van Deuren MG, Loch TP, Faisal M (2017) The Asian fish tapeworm *Schyzocotyle acheilognathi* is widespread in baitfish retail stores in Michigan, USA. *Parasites & Vectors* 10(1): 1–11. <https://doi.org/10.1186/s13071-017-2541-6>



- Boonthai T, Loch TP, Zhang Q, Van Deuren MG, Faisal M, Whelan GE, Herbst SJ (2018) Retail baitfish in Michigan Harbor serious fish viral pathogens. *Journal of Aquatic Animal Health* 30(4): 253–263. <https://doi.org/10.1002/aah.10034>
- Bowater RO, Wingfield M, Fisk A, Condon KML, Reid A, Prior H, Kulpa EC (2002) A parvo-like virus in cultured redclaw crayfish *Cherax quadricarinatus* from Queensland, Australia. *Diseases of Aquatic Organisms* 50: 79–86. <https://doi.org/10.3354/dao050079>
- Boyce WM, Kazacos EA, Kazacos KR, Engelhardt JA (1987) Pathology of pentastomid infections (*Sebekia mississippiensis*) in fish. *Journal of Wildlife Diseases* 23(4): 689–692. <https://doi.org/10.7589/0090-3558-23.4.689>
- Britton JR, Cucherousset J, Davies GD, Godard MJ, Copp GH (2010) Non-native fishes and climate change: Predicting species responses to warming temperatures in a temperate region. *Freshwater Biology* 55(5): 1130–1141. <https://doi.org/10.1111/j.1365-2427.2010.02396.x>
- Britton JR, Copp GH, Brazier M, Davies GD (2011) A modular assessment tool for managing introduced fishes according to risks of species and their populations, and impacts of management actions. *Biological Invasions* 13(12): 2847–2860. <https://doi.org/10.1007/s10530-011-9967-0>
- Brunner JL (2020) Pooled samples and eDNA-based detection can facilitate the “clean trade” of aquatic animals. *Scientific Reports* 10(1): 1–11. <https://doi.org/10.1038/s41598-020-66280-7>
- Bueno-Silva M, Boeger WA (2009) Neotropical Monogenoidea. 53. *Gyrodactylus corydori* sp. n. and redescription of *Gyrodactylus anisopharynx* (Gyrodactylidae: Gyrodactylidae), parasites of *Corydoras* spp. (Siluriformes: Callichthyidae) from southern Brazil. *Folia Parasitologica* 56(1): 13–20. <https://doi.org/10.14411/fp.2009.003>
- Bueno-silva M, Boeger WA, Pie MR (2011) Choice matters: Incipient speciation in *Gyrodactylus corydori* (Monogenoidea: Gyrodactylidae). *International Journal for Parasitology* 41(6): 657–667. <https://doi.org/10.1016/j.ijpara.2011.01.002>
- Callahan HA, Litaker RW, Noga EJ (2005) Genetic relationships among members of the *Ichthyobodo necator* complex: Implications for the management of aquaculture stocks. *Journal of Fish Diseases* 28(2): 111–118. <https://doi.org/10.1111/j.1365-2761.2004.00603.x>
- Camus AC, Dill JA, Rosser TG, Pote LM, Griffin MJ (2017) *Myxobolus axelrodi* n. sp. (Myxosporea: Myxobolidae) a parasite infecting the brain and retinas of the cardinal tetra *Paracheirodon axelrodi* (Teleostei: Characidae). *Parasitology Research* 116(1): 387–397. <https://doi.org/10.1007/s00436-016-5301-1>
- Chai JY, Hong SJ, Sohn WM (1985) Studies on intestinal trematodes in Korea. XVI. Infection status of loaches with the metacercariae of *Echinostoma hortense*. *Korean Journal of Parasitology* 23(1): 18–23. <https://doi.org/10.3347/kjp.1985.23.1.18>
- Chai JY, Van De N, Sohn WM (2012) Foodborne trematode metacercariae in fish from northern Vietnam and their adults recovered from experimental hamsters. *Korean Journal of Parasitology* 50(4): 317–325. <https://doi.org/10.3347/kjp.2012.50.4.317>
- Chan FT, Beatty SJ, Gilles Jr AS, Hill JE, Kozic S, Du L, Morgan DL, Pavia RTB, Therriault TW, Verreycken H, Vilizzi L, Wei H, Yeo DCJ, Zeng Y, Zięba G, Copp GH (2019) Leaving the fishbowl: The ornamental trade as a global vector for freshwater fish invasions. *Aquatic Ecosystem Health & Management* 22(4): 417–439. <https://doi.org/10.1080/14634988.2019.1685849>



- Chontanarith T, Wongsawad C (2010) Prevalence of *Haplorchis taichui* in field-collected snails: A molecular approach. *Korean Journal of Parasitology* 48(4): 343–346. <https://doi.org/10.3347/kjp.2010.48.4.343>
- Chontanarith T, Anucherngchai S, Tejangkura T (2018) The rapid detection method by polymerase chain reaction for minute intestinal trematodes: *Haplorchis taichui* in intermediate snail hosts based on 18s ribosomal DNA. *Journal of Parasitic Diseases: Official Organ of the Indian Society for Parasitology* 42(3): 423–432. <https://doi.org/10.1007/s12639-018-1020-0>
- Chou HY, Lo CF, Tung MC, Wang CH, Fukuda H, Sano T (1993) The General Characteristics of a birnavirus isolated from cultured loach (*Misgurnus anguillicaudatus*) in Taiwan. *Fish Pathology* 28(1): 1–7. <https://doi.org/10.3147/jsfp.28.1>
- Civanova K, Koyun M, Faculty L, Republic C (2013) The molecular and morphometrical description of a new diplozoid species from the gills of the *Garra rufa* (Heckel, 1843) (Cyprinidae) from Turkey – including a commentary on taxonomic division of Diplozoidae. 112: 3053–3062. <https://doi.org/10.1007/s00436-013-3480-6>
- Copp GH, Bianco PG, Bogutskaya NG, Erős T, Falka I, Ferreira MT, Fox MG, Freyhof J, Gozlan RE, Grabowska J, Kováč V, Moreno-Amich R, Naseka AM, Peñáz M, Povž M, Przybylski M, Robillard M, Russell IC, Stakėnas S, Šumer S, Vila-Gispert A, Wiesner C (2005a) To be, or not to be, a non-native freshwater fish? *Journal of Applied Ichthyology* 21(4): 242–262. <https://doi.org/10.1111/j.1439-0426.2005.00690.x>
- Copp GH, Wesley KJ, Vilizzi L (2005b) Pathways of ornamental and aquarium fish introductions into urban ponds of Epping Forest (London, England): The human vector. *Journal of Applied Ichthyology* 21(4): 263–274. <https://doi.org/10.1111/j.1439-0426.2005.00673.x>
- Copp GH, Templeton M, Gozlan RE (2007) Propagule pressure and the invasion risks of non-native freshwater fishes in Europe: A case study of England. *Journal of Fish Biology* 71(Supplement D): 148–159. <https://doi.org/10.1111/j.1095-8649.2007.01680.x>
- Copp GH, Vilizzi L, Mumford JD, Fenwick GV, Godard MJ, Gozlan RE (2009) Calibration of FISK, an invasive-ness screening tool for non-native freshwater fishes. *Risk Analysis* 29(3): 457–467. <https://doi.org/10.1111/j.1539-6924.2008.01159.x>
- Copp GH, Russell IC, Peeler EJ, Gherardi F, Tricarico E, MacLeod A, Cowx IG, Nunn AD, Occhipinti Ambrogi A, Savini D, Mumford JD, Britton JR (2016) European Non-native Species in Aquaculture Risk Analysis Scheme – a summary of assessment protocols and decision making tools for use of alien species in aquaculture. *Fisheries Management and Ecology* 23(1): 1–11. <https://doi.org/10.1111/fme.12074>
- Cornwell ER, Bellmund CA, Grocock GH, Wong PT, Hambury KL, Getchell RG, Bowser PL (2013) Fin and gill biopsies are effective nonlethal samples for detection of viral hemorrhagic septicemia virus genotype IVb. *Journal of Veterinary Diagnostic Investigation* 25(2): 203–209. <https://doi.org/10.1177/1040638713476865>
- Courtenay Jr WR (1999) Aquariums and water gardens as vectors of introduction. In: Claudi R, Leach JH (Eds) *Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts*. Lewis Publishers, Boca Raton, Florida, 127–128.
- Crossman EJ, Cudmore BC (1999) Summary of North American fish introductions through the aquarium/horticulture trade. In: Claudi R, Leach JH (Eds) *Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts*. Lewis Publishers, Boca Raton, 129–134.

- Davidovich N, Tobia P, Blum SE, Zina B, Rona G, Kaidar-Shwartz H, Zeev D, Efrat R (2019) *Mycobacterium gordonae* infecting redclaw crayfish *Cherax quadricarinatus*. *Diseases of Aquatic Organisms* 135(2): 169–174. <https://doi.org/10.3354/dao03392>
- De NC, Maity RN (1996) *Pseudocapillaria* (*Discocapillaria*) *margolisi* n. subg., n. sp. (Nematoda: Trichuroidea) from freshwater fishes of West Bengal, India. *Systematic Parasitology* 34(1): 49–52. <https://doi.org/10.1007/BF01531210>
- de Azevedo RK, Abdallah VD, Luque JL (2007) Community ecology of metazoan parasites of apaiari *Astronotus ocellatus* (Cope, 1872) (Perciformes: Cichlidae) from Guandu river, State of Rio de Janeiro, Brazil. *Revista Brasileira de Parasitologia Veterinária* 16: 15–20.
- de Azevedo RK, Abdallah VD, da Silva RJ, de Azevedo TMP, Martins ML, Luque JL (2012) Expanded description of *Lamproglana monodi* (Copepoda: Lernaeidae), parasitizing native and introduced fishes in Brazil. *Revista Brasileira de Parasitologia Veterinária* 21(3): 263–269. <https://doi.org/10.1590/S1984-29612012000300015>
- Dechruska W, Krailas D (2007) Trematode infections of the freshwater snail family Thiariidae in the Khek River, Thailand. *The Southeast Journal of Tropical Medicine and Public Health* 38: 1016–1028.
- Dey VK (2016) The global trade in ornamental fish. *Infofish International* 4: 52–55. <https://www.bassleer.com/ornamentalfishexporters/wp-content/uploads/sites/3/2016/12/GLOBAL-TRADE-IN-ORNAMENTAL-FISH.pdf>
- Ditrich O, Scholz T, Giboda M (1990) Occurrence of some medically important flukes (Trematoda: Opisthorchiidae and Heterophyidae) in Nam Ngum water reservoir, Laos. *The Southeast Asian Journal of Tropical Medicine and Public Health* 21: 482–488.
- Dove ADM (2000) Richness patterns in the parasite communities of exotic poeciliid fishes. *Parasitology* 120(6): 609–623. <https://doi.org/10.1017/S0031182099005958>
- Dove ADM, Ernst I (1998) Concurrent invaders - Four exotic species of Monogenea now established on exotic freshwater fishes in Australia. *International Journal for Parasitology* 28(11): 1755–1764. [https://doi.org/10.1016/S0020-7519\(98\)00134-9](https://doi.org/10.1016/S0020-7519(98)00134-9)
- Duggan IC, Rixon CA, MacIsaac HJ (2006) Popularity and propagule pressure: Determinants of introduction and establishment of aquarium fish. *Biological Invasions* 8(2): 377–382. <https://doi.org/10.1007/s10530-004-2310-2>
- Edgerton BF, Webb R, Anderson IG, Kulpa EC (2000) Description of a presumptive hepatopancreatic reovirus, and a putative gill parvovirus, in the freshwater crayfish *Cherax quadricarinatus*. *Diseases of Aquatic Organisms* 41: 83–90. <https://doi.org/10.3354/dao041083>
- Eide KE, Miller-Morgan T, Heidel JR, Kent ML, Bildfell RJ, LaPatra S, Watson G, Jin L (2011) Investigation of Koi Herpesvirus Latency in Koi. *Journal of Virology* 85(10): 4954–4962. <https://doi.org/10.1128/JVI.01384-10>
- Emde S, Kochmann J, Kuhn T, Dörge DD, Plath M, Miesen FW, Klimpel S (2016) Cooling water of power plant creates “hot spots” for tropical fishes and parasites. *Parasitology Research* 115(1): 85–98. <https://doi.org/10.1007/s00436-015-4724-4>
- Evers HG, Pinnegar JK, Taylor MI (2019) Where are they all from? – sources and sustainability in the ornamental freshwater fish trade. *Journal of Fish Biology* 94: 909–916. <https://doi.org/10.1111/jfb.13930>



- Forest JJH, King SD, Cone DK (2009) Occurrence of *Glugea pimephales* in planktonic larvae of fathead minnow in Algonquin Park, Ontario. *Journal of Aquatic Animal Health* 21(3): 164–166. <https://doi.org/10.1577/H08-057.1>
- Foster R, Peeler E, Bojko J, Clark PF, Morrith D, Roy HE, Stebbing P, Tidbury HJ, Wood LE, Bass D (2021) Pathogens co-transported with invasive non-native aquatic species: Implications for risk analysis and legislation. *NeoBiota* 69: 79–102. <https://doi.org/10.3897/neobiota.71358>
- Garcia F, Fujimoto RY, Martins ML, Moraes FR (2009) Parasitos protozoários de *Xiphophorus* sp. (Poeciliidae) e a relação deles com as características da água. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia* 61: 156–162. <https://doi.org/10.1590/S0102-09352009000100022>
- Girisha SK, Kushala KB, Nithin MS, Puneeth TG, Naveen Kumar BT, Vinay TN, Suresh T, Ajay SK, Venugopal MN, Ramesh KS (2021) First report of the infectious spleen and kidney necrosis virus (ISKNV) infection in ornamental fishes in India. *Transboundary and Emerging Diseases* 68(2): 964–972. <https://doi.org/10.1111/tbed.13793>
- Go J, Waltzek TB, Subramaniam K, Yun SC, Groff JM, Anderson IG, Chong R, Shirley I, Schuh JCL, Handler JH, Tweedie A, Whittington RJ (2016) Detection of infectious spleen and kidney necrosis virus (ISKNV) and turbot reddish body iridovirus (TRBIV) from archival ornamental fish samples. *Diseases of Aquatic Organisms* 122(2): 105–123. <https://doi.org/10.3354/dao03068>
- Gomez DK, Dong JL, Gun WB, Hee JY, Nam SS, Hwa YY, Cheol YH, Jun HP, Se CP (2006) Detection of betanodaviruses in apparently healthy aquarium fishes and invertebrates. *Journal of Veterinary Science (Suwon-si, Korea)* 7(4): 369–374. <https://doi.org/10.4142/jvs.2006.7.4.369>
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25(15): 1965–1978. <https://doi.org/10.1002/joc.1276>
- Hood Y, Sadler J, Poldy J, Starkey CS, Robinson AP (2019) Biosecurity system reforms and the development of a risk-based surveillance and pathway analysis system for ornamental fish imported into Australia. *Preventive Veterinary Medicine* 167: 159–168. <https://doi.org/10.1016/j.prevetmed.2018.11.006>
- Hoshino ÉM, Hoshino MDFG, Tavares-Dias M (2018) Parasites of ornamental fish commercialized in Macapá, Amapá State (Brazil). *Revista Brasileira de Parasitologia Veterinária* 27: 75–80. <https://doi.org/10.1590/S1984-29612018002>
- Hsieh C, Huang C, Pan Y (2016) Crayfish plague *Aphanomyces astaci* detected in redclaw crayfish, *Cherax quadricarinatus* in Taiwan. *Journal of Invertebrate Pathology* 136: 117–123. <https://doi.org/10.1016/j.jip.2016.03.015>
- Hudson PL, Bowen CA II (2002) First Record of *Neoergasilus japonicus* (Poecilostomatoida : Ergasilidae), a parasitic copepod new to the Laurentian Great Lakes. *The Journal of Parasitology* 88(4): 657–663. [https://doi.org/10.1645/0022-3395\(2002\)088\[0657:FRONJP\]2.0.CO;2](https://doi.org/10.1645/0022-3395(2002)088[0657:FRONJP]2.0.CO;2)
- Humphrey JD, Lancaster C, Gudkovs N, McDonald W (1986) Exotic bacterial pathogens *Edwardsiella tarda* and *Edwardsiella ictaluri* from imported ornamental fish *Betta splendens*

- and *Puntius conchoni*, respectively: Isolation and quarantine significance. Australian Veterinary Journal 63(11): 369–371. <https://doi.org/10.1111/j.1751-0813.1986.tb02900.x>
- Iwanowicz LR, Goodwin AE (2002) A new bacilliform fathead minnow rhabdovirus that produces syncytia in tissue culture. Archives of Virology 147(5): 899–915. <https://doi.org/10.1007/s00705-001-0793-z>
- Jithila PJ, Prasadani PK (2018) Description of *Tetracotyle wayanadensis* n. sp. (Digenea: Strigeidae) metacercaria infecting six species of freshwater fishes from Western Ghats, India. Journal of Parasitic Diseases: Official Organ of the Indian Society for Parasitology 42(2): 226–231. <https://doi.org/10.1007/s12639-018-0988-9>
- Jun JW, Kim JH, Gomez DK, Choresca Jr CH, Han JE, Shin SP, Park SC (2010) Occurrence of tetracycline-resistant *Aeromonas hydrophila* infection in Korean cyprinid loach (*Misgurnus anguillicaudatus*). African Journal of Microbiological Research 4: 849–855.
- Keller RP, Lodge DM (2007) Species invasions from commerce in live aquatic organisms: Problems and possible solutions. Bioscience 57(5): 428–436. <https://doi.org/10.1641/B570509>
- Kim JH, Hayward CJ, Joh SJ, Heo GJ (2002) Parasitic infections in live freshwater tropical fishes imported to Korea. Diseases of Aquatic Organisms 52: 169–173. <https://doi.org/10.3354/dao052169>
- Kim SG, Giri SS, Kim SW, Kwon J, Lee S, Park SC (2020) First isolation and characterization of *chryseobacterium cucumeris* sknucl01, isolated from diseased pond loach (*Misgurnus anguillicaudatus*) in Korea. Pathogens (Basel, Switzerland) 9(5): 1–15. <https://doi.org/10.3390/pathogens9050397>
- King TA (2019) Wild caught ornamental fish: A perspective from the UK ornamental aquatic industry on the sustainability of aquatic organisms and livelihoods. Journal of Fish Biology 94(6): 925–936. <https://doi.org/10.1111/jfb.13900>
- Knipes AK, Janovy Jr J (2009) Community structure and seasonal dynamics of *Dactylogyrus* Spp. (monogenea) on the fathead minnow (*Pimephales promelas*) from the salt valley watershed, Lancaster County, Nebraska. The Journal of Parasitology 95(6): 1295–1305. <https://doi.org/10.1645/GE-2166.1>
- Koda SA, Subramaniam K, Francis-Floyd R, Yanong RP, Frasca Jr S, Groff JM, Popov VL, Fraser WA, Yan A, Mohan S, Waltzek TB (2018) Phylogenomic characterization of two novel members of the genus *Megalocytyvirus* from archived ornamental fish samples. Diseases of Aquatic Organisms 130(1): 11–14. <https://doi.org/10.3354/dao03250>
- Kritsky DC, Van Every LR, Boeger WA (1996) Neotropical monogenoidea. 27. Two new species of *Telethecium* gen. n. from the nasal cavities of central amazonian fishes and a redescription of *Kritskyia moravec* Kohn, 1990 (Dactylogyridae, Ancyrocephalinae). Comparative Parasitology 63: 35–41.
- Kwon SR, Kim HJ (2011) *Thelohanellus misgurni* (Kudo, 1919) infection on the fins of Chinese muddy loach *Misgurnus mizolepis*. Journal of Fish Pathology 24(2): 167–171. <https://doi.org/10.7847/jfp.2011.24.2.167>
- Langenmayer MC, Lewisch E, Gotesman M, Hoedt W, Schneider M, El-Matbouli M, Hermanns W (2015) Cutaneous infection with *Dermocystidium salmonis* in cardinal tetra, *Paracheirodon axelrodi* (Schultz, 1956). Journal of Fish Diseases 38(5): 503–506. <https://doi.org/10.1111/jfd.12281>



- Lari E, Adams RV, Cone DK, Goater CP, Pyle GG (2016) *Dactylogyrus olfactorius* n. sp. (Monogenea, Dactylogyridae) from the olfactory chamber of the fathead minnow, *Pimephales promelas* Rafinesque (Cyprinidae). *Systematic Parasitology* 93(6): 575–581. <https://doi.org/10.1007/s11230-016-9649-5>
- Leal MC, Vaz MCM, Puga J, Rocha RJM, Brown C, Rosa R, Calado R (2016) Marine ornamental fish imports in the European Union: An economic perspective. *Fish and Fisheries* 17(2): 459–468. <https://doi.org/10.1111/faf.12120>
- Liu C, Olden JD (2017) Heads you win, tails you lose: Life-history traits predict invasion and extinction risk of the world's freshwater fishes. *Aquatic Conservation* 27(4): 773–779. <https://doi.org/10.1002/aqc.2740>
- Logez M, Bady P, Pont D (2012) Modelling the habitat requirement of riverine fish species at the European scale: Sensitivity to temperature and precipitation and associated uncertainty. *Ecology Freshwater Fish* 21(2): 266–282. <https://doi.org/10.1111/j.1600-0633.2011.00545.x>
- López-Olmeda JF, Sánchez-Vázquez FJ (2011) Thermal biology of zebrafish (*Danio rerio*). *Journal of Thermal Biology* 36(2): 91–104. <https://doi.org/10.1016/j.jtherbio.2010.12.005>
- Lymbery AJ, Morine M, Kanani HG, Beatty SJ, Morgan DL (2014) Co-invaders: The effects of alien parasites on native hosts. *International Journal for Parasitology. Parasites and Wildlife* 3(2): 171–177. <https://doi.org/10.1016/j.ijppaw.2014.04.002>
- Majtán J, Černý J, Ofúkana A, Takáč P, Kozánek M (2012) Mortality of therapeutic fish *Garra rufa* caused by *Aeromonas sobria*. *Asian Pacific Journal of Tropical Biomedicine* 2(2): 85–87. [https://doi.org/10.1016/S2221-1691\(11\)60197-4](https://doi.org/10.1016/S2221-1691(11)60197-4)
- Marcogliese DJ (1991) Seasonal occurrence of *Lernaea cyprinacea* on fishes in Belew Lake, North Carolina. *The Journal of Parasitology* 77(2): 326–327. <https://doi.org/10.2307/3283108>
- Marcos-López M, Gale P, Oidtmann BC, Peeler EJ (2010) Assessing the impact of climate change on disease emergence in freshwater fish in the United Kingdom. *Transboundary and Emerging Diseases* 57(5): 293–304. <https://doi.org/10.1111/j.1865-1682.2010.01150.x>
- Martins ML, Tavares-Dias M, Janik AJ, Kent ML, Jerônimo GT (2017) Hematology and condition factor of tui chub and fathead minnow parasitized by nematode from Upper Klamath Lake, Oregon, USA. *Diseases of Aquatic Organisms* 126(3): 257–262. <https://doi.org/10.3354/dao03168>
- McKoy SA, Hyslop EJ, Robinson RD (2011) Associations between two trematode parasites, an ectosymbiotic annelid, and thiara (*Tarebia*) *granifera* (Gastropoda) in Jamaica. *The Journal of Parasitology* 97(5): 828–832. <https://doi.org/10.1645/GE-2494.1>
- Mendoza-Franco EF, Aguirre-Macedo ML, Vidal-Martínez VM (2007) New and previously described species of dactylogyridae (Monogenoidea) from the gills of Panamanian freshwater fishes (Teleostei). *The Journal of Parasitology* 93(4): 761–771. <https://doi.org/10.1645/GE-1068R.1>
- Mendoza-Franco EF, Scholz T, Rozkošná P (2010) *Tucunarella* n. gen. and other dactylogyrids (monogenoidea) from cichlid fish (perciformes) from peruvian Amazonia. *Journal of Parasitology* 96(3): 491–498. <https://doi.org/10.1645/GE-2213.1>
- Mirzaei M (2015) Prevalence and histopathologic study of *Lernaea cyprinacea* in two species of ornamental fish (*Poecilia latipinna* and *Xiphophorus helleri*) in Kerman, South-East Iran. *Turkiye Parazitoloji Dergisi* 39(3): 222–226. <https://doi.org/10.5152/tpd.2015.3960>

- Mitchell AJ, Smith CE, Hoffman GL (1982) Pathogenicity and histopathology of an unusually intense infection of white grubs (*Posthodiplostomum m. minimum*) in the fathead minnow (*Pimephales promelas*). *Journal of Wildlife Diseases* 18(1): 51–57. <https://doi.org/10.7589/0090-3558-18.1.51>
- Mood SM, Mousavi HAE, Mokhayer BA, Ahmadi M, Soltani M, Sharifpour I (2010) *Centrocestus formosanus* metacercarial infection of four ornamental fish species imported into Iran. *Bulletin of the European Association of Fish Pathologists* 30: 146–149.
- Mood S M., Rassouli M (2016) Monogenean infestations of arowana (*Osteoglossum bicirrhosum*) and cat fish (*Hypostomus plecostomus*). *Iranian Journal of Fisheries Science* 15: 606–612. <http://hdl.handle.net/1834/37643>
- Mor SK, Phelps NBD, Ng TFF, Subramaniam K, Primus A, Armien AG, McCann R, Puzach C, Waltzek TB, Goyal SM (2017) Genomic characterization of a novel calicivirus, FHMCV-2012, from baitfish in the USA. *Archives of Virology* 162(12): 3619–3627. <https://doi.org/10.1007/s00705-017-3519-6>
- Moravec F, Justine JL (2006) *Camallanus cotti* (Nematoda: Camallanidae), an introduced parasite of fishes in New Caledonia. *Folia Parasitologica* 53(4): 287–296. <https://doi.org/10.14411/fp.2006.035>
- Moravec F, Jiménez-García MI, Salgado-Maldonado G (1998) New observations on *Mexiconema cichlasomae* (Nematoda: Dracunculoidea) from fishes in Mexico. *Parasite (Paris, France)* 5(3): 289–293. <https://doi.org/10.1051/parasite/1998053289>
- Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463(7282): 747–756. <https://doi.org/10.1038/nature08823>
- Mousavi HAE, Omidzahir S, Soltani M, Shayan P, Ebrahimzadeh E, Mousavi S, Hoseini M (2013) Morphometrical and molecular characterization of *Gyrodactylus cichlidarum* (Gyrodactylidae) from *Astronotus ocellatus* (Cichlidae) in Iran. *Comparative Clinical Pathology* 22(6): 1093–1097. <https://doi.org/10.1007/s00580-012-1534-2>
- Nagasawa K, Torii R-I (2014) The parasitic copepod *Lernaea cyprinacea* from freshwater fishes, including alien species (*Gambusia affinis* and *Rhodeus ocellatus ocellatus*), in central Japan. *Biosphere Science* 53: 27–31.
- Naimi B, Araújo MB (2016) Sdm: A reproducible and extensible R platform for species distribution modelling. *Ecography* 39(4): 368–375. <https://doi.org/10.1111/ecog.01881>
- Nawa Y, Noda S, Uchiyama-Nakamura F, Ishiwata K (2001) Current status of food-borne parasitic zoonoses in Japan. *The Southeast Asian Journal of Tropical Medicine and Public Health* 32: 4–7.
- Nazarenko L, Schmidt GA, Miller RL, Tausnev N, Kelley M, Reudy R, Russell GL, Aleinov I, Bauer M, Bauer S, Bleck R, Canuto V, Cheng Y, Clune TL, Del Genio AD, Faluvegi G, Hansen JE, Healy RJ, Kiang NY, Koch D, Lacis AA, LeGrande AN, Lerner J, Lo KK, Menon S, Oinas V, Perlwitz J, Puma MJ, Rind D, Romanou A, Sato M, Shindell DT, Sun S, Tsigaridis K, Unger N, Voulgarakis A, Yao MS, Zhang J (2015) Future climate change under RCP emission scenarios with GISS ModelE2. *Journal of Advances in Modeling Earth Systems* 7(1): 244–267. <https://doi.org/10.1002/2014MS000403>



- Neves LR, Pereira FB, Tavares-Dias M, Luque JL (2013) Seasonal influence on the parasite fauna of a wild population of *Astronotus ocellatus* (Perciformes: Cichlidae) from the Brazilian Amazon. *The Journal of Parasitology* 99(4): 718–721. <https://doi.org/10.1645/12-84.1>
- Ng TH, Tan SK, Wong WH, Meier R, Chan SY, Tan HH, Yeo DCJ (2016) Molluscs for sale: Assessment of freshwater gastropods and bivalves in the ornamental pet trade. *PLoS ONE* 11(8): 1–23. <https://doi.org/10.1371/journal.pone.0161130>
- Ngamniyom A, Sriyapai T, Sriyapai P, Panyarachun B (2019) Contributions to the knowledge of *Pseudolevinseniella* (Trematoda: Digenea) and temnocephalans from alien cray fish in natural freshwaters of Thailand. *Heliyon* 5(12): e02990. <https://doi.org/10.1016/j.heliyon.2019.e02990>
- Nitta M, Nagasawa K (2018) *Gyrodactylus medaka* n. sp. (Monogenea: Gyrodactylidae) parasitic on wild and laboratory-reared medaka *Oryzias latipes* (Beloniformes: Adrianichthyidae) in Japan. *Parasitology International* 67(5): 651–658. <https://doi.org/10.1016/j.parint.2018.06.010>
- Novotný L, Dvořák P (2001) Manifestation of mycobacteriosis in cardinal tetras *Paracheirodon axelrodi* (Schultz, 1956) during the *Pleistophora hyphessobryconis* (Schaperclaus, 1941) infection. *Folia Veterinaria* 50: 80–82.
- OATA (2020) Annual Review 2019/20: Reflecting on a changing world.
- OATA (2021) Apple snails can return to GB Aquariums after restrictions lift. <https://ornamentalfish.org/apple-snails-can-return-to-gb-after-restriction>
- Ohyama F, Okino T, Ushirogawa H (2001) *Massaliatrema misgurni* n. sp. (Trematoda: Heterophyidae) whose metacercariae encyst in loaches (*Misgurnus anguillicaudatus*). *Parasitology International* 50(4): 267–271. [https://doi.org/10.1016/S1383-5769\(01\)00084-8](https://doi.org/10.1016/S1383-5769(01)00084-8)
- OIE (Office International des Epizooties) (2019) Infection with koi herpesvirus. Manual of diagnostic tests for aquatic animals. [https://www.oie.int/index.php?id=2439&L=0&htmlfile=chapitre\\_koi\\_herpesvirus.htm](https://www.oie.int/index.php?id=2439&L=0&htmlfile=chapitre_koi_herpesvirus.htm)
- Oliveira MSB, Corrêa LL, Tavares-Dias M (2019) Helminthic endofauna of four species of fish from lower Jari river, a tributary of the Amazon basin in Brazil. *Boletim do Instituto de Pesca* 45(1): e393. <https://doi.org/10.20950/1678-2305.2019.45.1.393>
- Owens L, McElnea C (2000) Natural infection of the redclaw crayfish *Cherax quadricarinatus* with presumptive spawner-isolated mortality virus. *Diseases of Aquatic Organisms* 40: 219–223. <https://doi.org/10.3354/dao040219>
- Padilla D, Williams S (2004) Beyond ballast water: Aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. *Frontiers in Ecology and the Environment* 2(3): 131–138. [https://doi.org/10.1890/1540-9295\(2004\)002\[0131:BBWAAO\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2004)002[0131:BBWAAO]2.0.CO;2)
- Paller VGV, Macaraig JRM, Verona RT, Estaño LA (2019) Cercarial fauna of freshwater snails in selected agricultural areas in Laguna, Philippines. *Helminthologia (Poland)* 56(1): 81–86. <https://doi.org/10.2478/helm-2018-0040>
- Peeler EJ, Oidtmann BC, Midtlyng PJ, Miossec L, Gozlan RE (2011) Non-native aquatic animals introductions have driven disease emergence in Europe. *Biological Invasions* 13(6): 1291–1303. <https://doi.org/10.1007/s10530-010-9890-9>
- Peyghan R, Rahnema R, Dezfily ZT, Shokoohmand M (2019) *Achlya* infection in an oscar (*Astronotus ocellatus*) with typical symptoms of saprolegniosis. *Veterinary Research Forum* 10: 89–92.

- Phelps NBD, Mor SK, Armien AG, Batts W, Goodwin AE, Hopper L, McCann R, Ng TFF, Puzach C, Waltzek TB, Delwart E, Winton J, Goyal SM (2014) Isolation and molecular characterization of a novel picornavirus from baitfish in the USA. PLoS ONE 9(2): e87593. <https://doi.org/10.1371/journal.pone.0087593>
- Piazza RS, Martins ML, Guiraldelli L, Yamashita MM (2006) Parasitic diseases of freshwater ornamental fishes commercialized in Florianópolis, Santa Catarina, Brazil. Boletim do Instituto de Pesca 32: 51–57.
- Pie MR, Boeger WA (2006) Density-dependent topographical specialization in *Gyrodactylus anisopharynx* (Monogeneoidea, Gyrodactylidae): Boosting transmission or evading competition? Journal of Parasitology 92(3): 459–463. <https://doi.org/10.1645/GE-641.1>
- Pinder AC, Gozlan RE (2003) Sunbleak and topmouth gudgeon – two new additions to Britain’s freshwater fishes. British Wildlife (December): 77–83.
- Pinheiro RHDS, Tavares-Dias M, Giese EG (2019) Helminth parasites in two populations of *Astronotus ocellatus* (Cichliformes: Cichlidae) from the eastern amazon, northern brazil. Revista Brasileira de Parasitologia Veterinaria 28: 425–431. <https://doi.org/10.1590/S1984-29612019052>
- Pinnegar JK, Murray JM (2019) Understanding the United Kingdom marine aquarium trade – a mystery shopper study of species on sale. Journal of Fish Biology 94: 917–924. <https://doi.org/10.1111/jfb.13941>
- Paul SE, Romero NG, Barbeito CG (2010) Distribution of the exotic parasite, *Lernaea cyprinacea* (Copepoda, Lernaeidae) in Argentina. Bulletin of the European Association of Fish Pathologists 30: 65–73.
- Popazoglo F, Boeger WA (2016) Neotropical Monogeneoidea 37. Redescription of *Gyrodactylus superbus* (Szidat, 1973) comb. n. and description of two new species of *Gyrodactylus* (Gyrodactylidea: Gyrodactylidae) from *Corydoras paleatus* and *C. ehrhardti* (Teleostei: Siluriformes: Callichthyidae) of Southern Brazil. Folia Parasitologica 47(2): 105–110. <https://doi.org/10.14411/fp.2000.022>
- Pradhan PK, Rathore G, Sood N, Swaminathan TR, Yadav MK, Verma DK, Chaudhary DK, Abidi R, Punia P, Jena JK (2014) Emergence of epizootic ulcerative syndrome: Large-scale mortalities of cultured and wild fish species in Uttar Pradesh, India. Current Science 106: 1711–1718. <http://www.jstor.org/stable/24103006>
- Qin L, Zhu M, Xu J (2014) First report of *Shewanella* sp. and *Listonella* sp. infection in freshwater cultured loach, *Misgurnus anguillicaudatus*. Aquaculture Research 45(4): 602–608. <https://doi.org/10.1111/j.1365-2109.2012.03260.x>
- Qiu JH, Zhang Y, Zhang XX, Gao Y, Li Q, Chang QC, Wang CR (2017) Metacercaria infection status of fishborne zoonotic trematodes, except for *Clonorchis sinensis* in fish from the Heilongjiang Province, China. Foodborne Pathogens and Disease 14(8): 440–446. <https://doi.org/10.1089/fpd.2016.2249>
- Rauque C, Viozzi G, Flores V, Vega R, Waicheim A, Salgado-maldonado G (2018) Helminth parasites of alien freshwater fishes in Patagonia (Argentina). International Journal for Parasitology: Parasites and Wildlife 7(3): 369–379. <https://doi.org/10.1016/j.ijppaw.2018.09.008>



- Řehulka J, Kolařík M, Hubka V (2017) Disseminated infection due to *Exophiala pisciphila* in Cardinal tetra, *Paracheirodon axelrodi*. *Journal of Fish Diseases* 40(8): 1015–1024. <https://doi.org/10.1111/jfd.12577>
- Reyda FB, Wells SM, Ermolenko AV, Zietara MS, Lumme JI (2020) Global parasite trafficking: Asian *Gyrodactylus* (Monogenea) arrived to the U.S.A. via invasive fish *Misgurnus anguillicaudatus* as a threat to amphibians. *Biological Invasions* 22(2): 391–402. <https://doi.org/10.1007/s10530-019-02097-4>
- Rhee JK, Baek BK, Lee SB, Koh HB (1983) Epidemiological studies of *Clonorchis Sinensis* in Mangyeong riverside areas in Korea. *Korean Journal of Parasitology* 21(2): 157–166. <https://doi.org/10.3347/kjp.1983.21.2.157>
- Rhyne AL, Tlusty MF, Schofield PJ, Kaufman L, Morris JA, Bruckner AW (2012) Revealing the appetite of the marine aquarium fish trade: The volume and biodiversity of fish imported into the United States. *PLoS ONE* 7(5): e35808. <https://doi.org/10.1371/journal.pone.0035808>
- Rhyne AL, Tlusty MF, Szczebak JT, Holmberg RJ (2017) Expanding our understanding of the trade in marine aquarium animals. *PeerJ* 5: e2949. <https://doi.org/10.7717/peerj.2949>
- Rodrigues MNG, Dias MKR, Marinho RDB, Tavares-Dias M (2014) Parasite Diversity Of *Osteoglossum Bicirrhosum*, An Osteoglossidae Fish From Amazon. *Neotropical Helminthology* 8.
- Romero X, Turnbull JF, Jiménez R (2000) Ultrastructure and cytopathology of a rickettsia-like organism causing systemic infection in the redclaw crayfish, *Cherax quadricarinatus* (Crustacea: Decapoda), in Ecuador. *Journal of Invertebrate Pathology* 76(2): 95–104. <https://doi.org/10.1006/jipa.2000.4952>
- Ruane NM, Collins EM, Geary M, Swords D, Hickey C, Geoghegan F (2013) Isolation of *Streptococcus agalactiae* and an aquatic birnavirus from doctor fish *Garra rufa* L. *Irish Veterinary Journal* 66(1): 2–5. <https://doi.org/10.1186/2046-0481-66-16>
- Ruehl-Fehlert C, Bomke C, Dorgerloh M, Palazzi X, Rosenbruch M (2005) *Pleistophora* infestation in fathead minnows, *Pimephales promelas* (Rafinesque). *Journal of Fish Diseases* 28(11): 629–637. <https://doi.org/10.1111/j.1365-2761.2005.00661.x>
- Ryang YS (1990) Studies on *Echinostoma* spp. in the Chungju Reservoir and upper streams of the Namhan River. *Korean Journal of Parasitology* 28(4): 221–233. <https://doi.org/10.3347/kjp.1990.28.4.221>
- Sakuna K, Elliman J, Owens L (2017) Discovery of a novel Picornavirales, Chequa iflavivirus, from stressed redclaw crayfish (*Cherax quadricarinatus*) from farms in northern Queensland, Australia. *Virus Research* 238: 148–155. <https://doi.org/10.1016/j.virusres.2017.06.021>
- Sakuna K, Elliman J, Tzamouzaki A, Owens L (2018) A novel virus (order Bunyavirales) from stressed redclaw crayfish (*Cherax quadricarinatus*) from farms in northern Australia. *Virus Research* 250: 7–12. <https://doi.org/10.1016/j.virusres.2018.03.012>
- Salgado-Maldonado G (2013) Redescription of *Neoechinorhynchus* (*Neoechinorhynchus*) *golvani* Salgado-Maldonado, 1978 (Acanthocephala: Neoechinorhynchidae) and description of a new species from freshwater cichlids (Teleostei: Cichlidae) in Mexico. *Parasitology Research* 112(5): 1891–1901. <https://doi.org/10.1007/s00436-013-3374-7>

- Sanders JL, Watral V, Stidworthy MF, Kent ML (2016) Expansion of the known host range of the *Microsporidium*, *Pseudoloma neurophilia*. Zebrafish 13(S1): S102–S106. <https://doi.org/10.1089/zeb.2015.1214>
- Sandland GJ, Goater CP (2001) Parasite-Induced variation in host morphology: Brain-encysting trematodes in fathead minnows. The Journal of Parasitology 87(2): 267–272. [https://doi.org/10.1645/0022-3395\(2001\)087\[0267:PIVIHM\]2.0.CO;2](https://doi.org/10.1645/0022-3395(2001)087[0267:PIVIHM]2.0.CO;2)
- Sandland GJ, Goater CP, Danylchuk AJ (2001) Population dynamics of *Ornithodiplostomum ptychocheilus* metacercariae in fathead minnows (*Pimephales promelas*) from four northern-Alberta lakes. Journal of Parasitology 87(4): 744–748. [https://doi.org/10.1645/0022-3395\(2001\)087\[0744:PDOOPM\]2.0.CO;2](https://doi.org/10.1645/0022-3395(2001)087[0744:PDOOPM]2.0.CO;2)
- Schleppe JL, Goater CP (2004) Comparative life histories of two diplostomid trematodes, *Ornithodiplostomum ptychocheilus* and *Posthodiplostomum minimum*. Journal of Parasitology 90(6): 1387–1390. <https://doi.org/10.1645/GE-274R>
- Scholz T, Shimazu T, Olson PD, Nagasawa K (2001) Caryophyllidean tapeworms (Platyhelminthes: Eucestoda) from freshwater fishes in Japan. Folia Parasitologica 48(4): 275–288. <https://doi.org/10.14411/fp.2001.046>
- Scholz T, Oros M, Bazsalovicsová E, Brabec J, Waeschenbach A, Xi BW, Aydoğdu A, Besprozvannykh V, Shimazu T, Králová-Hromadová I, Littlewood DTJ (2014) Molecular evidence of cryptic diversity in *Paracaryophyllaeus* (Cestoda: Caryophyllidae), parasites of loaches (Cobitidae) in Eurasia, including description of *P. vladkai* n. sp. Parasitology International 63(6): 841–850. <https://doi.org/10.1016/j.parint.2014.07.015>
- Seo BS, Park YH, Chai JY, Hong SJ, Lee SH (1984) Studies on intestinal trematodes in Korea xiv. infection status of loaches with metacercariae of *Echinostoma cinetorchis* and their development in albino rats. Korean Journal of Parasitology 22(2): 181–189. <https://doi.org/10.3347/kjp.1984.22.2.181>
- Shamsi S, Stoddart A, Smales L, Wassens S (2019) Occurrence of *Contracaecum bancrofti* larvae in fish in the Murray-Darling Basin. Journal of Helminthology 93(05): 574–579. <https://doi.org/10.1017/S0022149X1800055X>
- Shin DS (1964) Epidemiological studies of *Clonorchis sinensis* prevailed in the peoples of Kyungpook Province. Korean Journal of Parasitology 2(1): 1–13. <https://doi.org/10.3347/kjp.1964.2.1.1>
- Sicuro B, Pastorino P, Barbero R, Barisone S, Dellerba D, Menconi V, Righetti M, De Vita V, Prearo M (2020) Prevalence and antibiotic sensitivity of bacteria isolated from imported ornamental fish in Italy: A translocation of resistant strains? Preventive Veterinary Medicine 175: e104880. <https://doi.org/10.1016/j.prevetmed.2019.104880>
- Smales LR, Aydogdu A, Emre Y (2012) Pomphorhynchidae and Quadrigyridae (Acanthocephala), including a new genus and species (Pallisentinae), from freshwater fishes, cobitidae and cyprinodontidae, in Turkey. Folia Parasitologica 59(3): 162–166. <https://doi.org/10.14411/fp.2012.022>
- Sohn W-M, Kho W-G, Lee SH (1993) Larval *Gnathostoma nipponicum* found in the imported Chinese loaches. Korean Journal of Parasitology 31(4): 347–352. <https://doi.org/10.3347/kjp.1993.31.4.347>



- Sokolova YY, Overstreet RM (2018) A new microsporidium, *Apotasporea heleios* n. g., n. sp., from the Riverine grass shrimp *Palaemonetes paludosus* (Decapoda: Caridea: Palaemonidae). *Journal of Invertebrate Pathology* 157: 125–135. <https://doi.org/10.1016/j.jip.2018.05.007>
- Sreedharan K, Philip R, Singh ISB (2011) Isolation and characterization of virulent *Aeromonas veronii* from ascitic fluid of oscar *Astronotus ocellatus* showing signs of infectious dropsy. *Diseases of Aquatic Organisms* 94(1): 29–39. <https://doi.org/10.3354/dao02304>
- Stevens GC (1992) The elevational gradient in altitudinal range: An extension of Rapoport's latitudinal rule to altitude. *American Naturalist* 140(6): 893–911. <https://doi.org/10.1086/285447>
- Tahir UBIN, Deng Q, Li SEN, Liu Y, Wang ZHE, Gu Z (2017) First record of a new epibionts suctorian ciliate *Tokophrya huangmeiensis* sp. n. (Ciliophora, Phyllopharyngea) from redclaw crayfish *Cherax quadricarinatus* von Martens 1868. *Zootaxa* 4269(2): 287–295. <https://doi.org/10.11646/zootaxa.4269.2.7>
- Taraschewski H (2006) Hosts and parasites as aliens. *Journal of Helminthology* 80(2): 99–128. <https://doi.org/10.1079/JOH2006364>
- Tavakol S, Luus-Powell WJ, Smit WJ, Baker C, Hoffman A, Halajian A (2016) First introduction of two Australian temnocephalan species into Africa with an alien host: Double trouble. *Journal of Parasitology* 102(6): 653–658. <https://doi.org/10.1645/15-936>
- Tavares-Dias M, Neves LR (2017) Diversity of parasites in wild *Astronotus ocellatus* (Perciformes, cichlidae), an ornamental and food fish in Brazil. *Anais da Academia Brasileira de Ciências* 89(3 suppl): 2305–2315. <https://doi.org/10.1590/0001-3765201720160700>
- Tavares-Dias M, Lemos JRG, Martins ML (2010) Parasitic fauna of eight species of ornamental freshwater fish species from the middle Negro River in the Brazilian Amazon Region. *Revista Brasileira de Parasitologia Veterinária* 19(2): 29–33. <https://doi.org/10.1590/S1984-29612010000200007>
- Tavares-Dias M, Sousa TJSM, Neves LR (2014) Infecções parasitárias em dois peixes bentopelágicos da amazônia: O aruanã *Osteoglossum bicirrhosum* (Osteoglossidae) e apaiari *Astronotus ocellatus* (Cichlidae). *Bioscience Journal* 30: 546–555.
- Taylor NGH, Way K, Jeffery KR, Peeler EJ (2010) The role of live fish movements in spreading koi herpesvirus throughout England and Wales. *Journal of Fish Diseases* 33(12): 1005–1007. <https://doi.org/10.1111/j.1365-2761.2010.01198.x>
- Taylor NGH, Norman RA, Way K, Peeler EJ (2011) Modelling the koi herpesvirus (KHV) epidemic highlights the importance of active surveillance within a national control policy. *Journal of Applied Ecology* 48(2): 348–355. <https://doi.org/10.1111/j.1365-2664.2010.01926.x>
- Taylor NGH, Peeler EJ, Denham KL, Crane CN, Thrush MA, Dixon PF, Stone DM, Way K, Oidtmann BC (2013) Spring viraemia of carp (SVC) in the UK: The road to freedom. *Preventive Veterinary Medicine* 111(1–2): 156–164. <https://doi.org/10.1016/j.prevet-med.2013.03.004>
- Thilakaratne IDSIP, Rajapaksha G, Hewakopara A, Rajapakse RPVJ, Faizal ACM (2003) Parasitic infections in freshwater ornamental fish in Sri Lanka. *Diseases of Aquatic Organisms* 54: 157–162. <https://doi.org/10.3354/dao054157>



- Thrush MA, Peeler EJ (2013) A model to approximate lake temperature from gridded daily air temperature records and its application in risk assessment for the establishment of fish diseases in the uk. *Transboundary and Emerging Diseases* 60(5): 460–471. <https://doi.org/10.1111/j.1865-1682.2012.01368.x>
- Tokşen E (2006) *Argulus foliaceus* (Crustacea: Branchiura) infestation on oscar, *Astronotus ocellatus* (Cuvier, 1829) and its treatment. *Ege Journal of Fisheries & Aquatic Sciences* 23: 177–179.
- Tolley-Jordan LR, Chadwick MA (2018) Effects of parasite infection and host body size on habitat associations of invasive aquatic snails: Implications for environmental monitoring. *Journal of Aquatic Animal Health* 31(1): 121–128. <https://doi.org/10.1002/aah.10059>
- Trujillo-González A, Becker JA, Vaughan DB, Hutson KS (2019a) Monogenean parasites infect ornamental fish imported to Australia. *Parasitology Research* 118(1): 383–384. <https://doi.org/10.1007/s00436-018-6156-4>
- Trujillo-González A, Edmunds RC, Becker JA, Hutson KS (2019b) Parasite detection in the ornamental fish trade using environmental DNA. *Scientific Reports* 9(1): 1–10. <https://doi.org/10.1038/s41598-019-41517-2>
- Tukmechi A, Hobbenaghi R, Rahmati Holasoo H, Morvaridi A (2009) *Streptococcosis* in a pet fish, *Astronotus ocellatus*: A case study. *World Academy of Science, Engineering and Technology* 37: 14–15.
- UK Government (2019) Copy of ILFA Aquarium Ornamentals Alphabetic Checklist. [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/919683/Copy\\_of\\_ILFA.\\_Aquarium\\_Ornamentals.\\_Alphabetic\\_checklist\\_for\\_BIPs.\\_\\_1\\_.ods](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919683/Copy_of_ILFA._Aquarium_Ornamentals._Alphabetic_checklist_for_BIPs.__1_.ods)
- UK Government (2021a) Introduce or keep non-native fish and shellfish. [www.gov.uk/guidance/introduce-or-keep-non-native-fish-and-shellfish](http://www.gov.uk/guidance/introduce-or-keep-non-native-fish-and-shellfish)
- UK Government (2021b) UK Risk Register Details for *Pomacea* spp. <https://secure.fera.defra.gov.uk/phiw/riskRegister/viewPestRisks.cfm?csref=6289>
- Ukong S, Krailas D, Dangprasert T, Channgarm P (2007) Studies on the morphology of cercariae obtained from freshwater snails at Erawan Waterfall, Erawan National Park, Thailand. *The Southeast Journal of Tropical Medicine and Public Health* 38: 303–312.
- Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: An overview. *Climatic Change* 109(1–2): 5–31. <https://doi.org/10.1007/s10584-011-0148-z>
- Vincent AG, Font WF (2003) Seasonal and yearly population dynamics of two exotic helminths, *Camallanus cotti* (nematoda) and *Bothriocephalus acheilognathi* (cestoda), parasitizing exotic fishes in Waianu Stream, O’ahu, Hawaii. *The Journal of Parasitology* 89(4): 756–760. <https://doi.org/10.1645/GE-90R>
- Volpe E, Mandrioli L, Errani F, Serratore P, Zavatta E, Rigillo A, Ciulli S (2019) Evidence of fish and human pathogens associated with doctor fish (*Garra rufa*, Heckel, 1843) used for cosmetic treatment. *Journal of Fish Diseases* 42(12): 1637–1644. <https://doi.org/10.1111/jfd.13087>
- Wang Z, Zhou T, Gu Z (2017a) New data of two trichodinid ectoparasites (Ciliophora: Trichodinidae) from farmed freshwater fishes in Hubei, China. *European Journal of Protistology* 60: 50–59. <https://doi.org/10.1016/j.ejop.2017.04.002>



- Wang ML, Chen HY, Shih HH (2017b) Occurrence and distribution of yellow grub trematodes (*Clinostomum complanatum*) infection in Taiwan. *Parasitology Research* 116(6): 1761–1771. <https://doi.org/10.1007/s00436-017-5457-3>
- Wang X, Li J, Cao X, Wang W, Luo Y (2019) Isolation, identification and characterisation of an emerging fish pathogen, *Acinetobacter pittii*, from diseased loach (*Misgurnus anguillicaudatus*) in China. *Antonie van Leeuwenhoek* 113(1): 21–32. <https://doi.org/10.1007/s10482-019-01312-5>
- Weichman MA, Janovy Jr J (2000) Parasite community structure in *Pimephales promelas* (pisces: Cyprinidae) from two converging streams. *Journal of Parasitology* 86(3): 654–656. [https://doi.org/10.1645/0022-3395\(2000\)086\[0654:PCSIPP\]2.0.CO;2](https://doi.org/10.1645/0022-3395(2000)086[0654:PCSIPP]2.0.CO;2)
- Weir M, Rajić A, Dutil L, Cernicchiaro N, Uhland FC, Mercier B, Tuševljak N (2012) Zoonotic bacteria, antimicrobial use and antimicrobial resistance in ornamental fish: A systematic review of the existing research and survey of aquaculture-allied professionals. *Epidemiology and Infection* 140(2): 192–206. <https://doi.org/10.1017/S0950268811001798>
- Wisenden BD, Martinez-Marquez JY, Gracia ES, McEwen DC (2012) High intensity and prevalence of two species of trematode metacercariae in the fathead minnow (*Pimephales promelas*) with no compromise of minnow anti-predator competence. *Journal of Parasitology* 98(4): 722–727. <https://doi.org/10.1645/GE-2454.1>
- Wood LE, Guilder J, Brennan ML, Birland NJ, Taleti V, Stinton N, Taylor NG, Thrush MA (2022) Biosecurity and the ornamental fish trade: A stakeholder perspective in England. *Journal of Fish Biology* 100(2): 352–365. <https://doi.org/10.1111/jfb.14928>
- Xu L, Wang T, Li F, Yang F (2016) Isolation and preliminary characterization of a new pathogenic iridovirus from redclaw crayfish *Cherax quadricarinatus*. *Diseases of Aquatic Organisms* 120(1): 17–26. <https://doi.org/10.3354/dao03007>
- Yamauchi T, Shimizu M (2013) New host and distribution records for the freshwater fish ectoparasite *Argulus japonicus* (Crustacea: Branchiura: Argulidae). *Comparative Parasitology* 80(1): 136–137. <https://doi.org/10.1654/4554.1>
- Yera H, Kuchta R, Brabec J, Peyron F, Dupouy-Camet J (2013) First identification of eggs of the Asian fish tapeworm *Bothriocephalus acheilognathi* (Cestoda: Bothriocephalidea) in human stool. *Parasitology International* 62(3): 268–271. <https://doi.org/10.1016/j.parint.2013.02.001>
- Yu J, Koo BH, Kim DH, Kim DW, Park SW (2015) *Aeromonas sobria* infection in farmed mud loach (*Misgurnus mizolepis*) in Korea, a bacteriological survey. *Majallah-i Tahqiqat-i Dampizishki-i Iran* 16: 194–201.
- Zanoni RG, Florio D, Fioravanti ML, Rossi M, Prearo M (2008) Occurrence of *Mycobacterium* spp. in ornamental fish in Italy. *Journal of Fish Diseases* 31(6): 433–441. <https://doi.org/10.1111/j.1365-2761.2008.00924.x>
- Zhang Y, Zhang Y, Na L, Wang WT, Xu WW, Gao DZ, Liu ZX, Wang CR, Zhu XQ (2014) Prevalence of *Clonorchis sinensis* infection in freshwater fishes in northeastern China. *Veterinary Parasitology* 204(3–4): 209–213. <https://doi.org/10.1016/j.vetpar.2014.05.007>
- Zhao Y, Tang F (2007) Trichodinid ectoparasites (Ciliophora: Peritricha) from *Misgurnus anguillicaudatus* (Cantor) and *Anodonta woodiana* (Lea) in China, with descriptions of two new species of Trichodina Ehrenberg, 1838. *Systematic Parasitology* 67(1): 65–72. <https://doi.org/10.1007/s11230-006-9070-6>



- Zięba G, Copp G, Davies G, Stebbing P, Wesley K, Britton R (2010) Recent releases and dispersal of non-native fishes in England and Wales, with emphasis on sunbleak *Leucaspius delineatus* (Heckel, 1843). *Aquatic Invasions* 5(2): 155–161. <https://doi.org/10.3391/ai.2010.5.2.04>
- Zizka A, Silvestro D, Andermann T, Azevedo J, Duarte Ritter C, Edler D, Farooq H, Herdean A, Ariza M, Scharn R, Svantesson S, Wengström N, Zizka V, Antonelli A (2019) CoordinateCleaner: Standardized cleaning of occurrence records from biological collection databases. *Methods in Ecology and Evolution* 10(5): 744–751. <https://doi.org/10.1111/2041-210X.13152>

## Supplementary material I

### Threats to UK freshwaters under climate change: Commonly traded aquatic ornamental species and their potential pathogens and parasites

Authors: Guilder J, Copp GH, Thrush M, Stinton N, Murphy D, Murray J, Tidbury HJ

Data type: Lists, Tables and Maps

Explanation note: This supplementary file provides a list of all websites used in the Google search, a table of all fish and invertebrate species observed as being sold in the UK and criteria for further analysis and a table of results for the pathogen and parasite screen based on laboratory studies (and the reference list for this table).

Copyright notice: This dataset is made available under the Open Database License (<http://opendatacommons.org/licenses/odbl/1.0/>). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: <https://doi.org/10.3897/neobiota.76.80215.suppl1>